Clim. Past, 20, 2595–2616, 2024
https://doi.org/10.5194/cp-20-2595-2024

Climate of the Past
Open Access

Droughts of the early 19th century (1790–1830) in the northeastern Iberian Peninsula: integration of historical and instrumental data for high-resolution reconstructions of extreme events

Josep Barriendos[1], **María Hernández**[2], **Salvador Gil-Guirado**[3], **Jorge Olcina Cantos**[2], **and Mariano Barriendos**[4]

[1]CREAF, Autonomous University of Barcelona, Barcelona, Spain
[2]Department of Regional Geographical Analysis and Physical Geography, University of Alicante, Alicante, Spain
[3]Department of Geography, University of Murcia, Murcia, Spain
[4]IDAEA-CSIC, Institute of Environmental Assessment and Water Research, Spanish Research Council, Barcelona, Spain

Correspondence: Josep Barriendos (j.barriendos@creaf.uab.cat)

Received: 20 March 2024 – Discussion started: 12 April 2024
Revised: 17 September 2024 – Accepted: 30 September 2024 – Published: 26 November 2024

Abstract. Drought represents a prevalent climate risk in the Mediterranean region. In the context of climate change, an increase in both frequency and intensity is anticipated over the next century. In order to effectively manage future scenarios where global warming overlays natural climate variability, a thorough analysis of the nature of droughts prior to the industrial age is crucial. This approach incorporates an extended temporal scale into the study of severe droughts, enabling the identification of low-frequency drought events that occurred before the instrumental period. The objective of this study is to examine the occurrence and magnitude of extreme droughts lasting over a year in the Spanish Mediterranean basin during the early 19th century (1790–1830). To achieve this objective, the research integrates the use of instrumental observations and information derived from historical documentary sources with daily to monthly resolutions (e.g., rogation ceremonies). The findings reveal that drought episodes were more frequent and severe during the early 19th century compared to the late 19th century. Moreover, drought episodes of similar severity were rare throughout the 20th century. Only in the current context of climate change, over the last 2 decades, has a pattern of high drought severity been identified that resembles the severity found during the early 19th century (especially between 1812 and 1825). This study underscores the presence of high variability in drought patterns over the last few centuries, justifying the need for intensified research on drought episodes with high temporal resolution for extended periods.

1 Introduction

Drought is a climate phenomenon defined as a prolonged absence of precipitation that can last for a few weeks to periods of up to several years (IDMP, 2022). According to the IPCC, drought is an exceptional period of water shortage for existing ecosystems and the human population (due to low rainfall, high temperature and/or wind) (IPCC, 2023). Despite their complexity as a natural phenomenon, droughts should not be confused with aridity, desertification, or other related natural risks such as forest fires or heat waves (Van Loon, 2015; IDMP, 2022). Drought, as a prolonged lack of precipitation, can be classified depending on the impacts on the environment and society, resulting in distinct types of droughts, such as meteorological, hydrological, agricultural and social droughts (Wilhite and Glantz, 1985).

Meteorological drought is defined as a prolonged period with abnormal rainfall deficit for a large region and for a long period of time (Mishra and Singh, 2010; IPCC, 2023). This absence of rain is transmitted to the hydrological system by affecting soil moisture and groundwater input, ultimately reducing surface water levels (Van Loon and Van Lanen, 2012).

Published by Copernicus Publications on behalf of the European Geosciences Union.

Thus, hydrological drought is defined as a period with large runoff and water deficits in rivers, lakes and reservoirs (Nalbantis, 2008; IPCC, 2023). It also has effects on groundwater and surface hydrology (Wilhite and Glantz, 1985; Mishra and Singh, 2010). This deficit causes a reduction in water supply to plant roots, leading to agricultural and ecological drought (Sivakumar et al., 2011; Van Loon, 2015; IPCC, 2023). The different impacts of drought mentioned above, such as the reduction in water levels or crop failures, have a direct effect on human societies (Van Loon, 2015).

Despite the importance of droughts and their capacity to seriously affect the economic and productive activities of societies, the level of knowledge about this natural phenomenon contrasts with that of other natural hazards (Van Loon and Van Lanen, 2012). For these reasons in this study is justified to conduct a more detailed and systematic study of drought events with historic perspective. It will also take into account the analysis of specific episodes of lower frequency and greater severity, which may provide additional information on long-term drought behavior in the Mediterranean region (Olcina, 2001a, b).

In general terms the Mediterranean climate in the Iberian Peninsula is characterized by a highly irregular rainfall at both inter-annual and intra-annual scales (Martín-Vide and Olcina Cantos, 2001). Another characteristic is the pronounced aridity during the warm season (summer) (WMO, 2023). Additionally, there are important variations in the intra-annual distribution of precipitation depending on the region (Martín-Vide, 1985). On the eastern side of Iberian Peninsula and the Balearic Islands, the Mediterranean climate type has two main varieties in relation to the seasonal distribution of rainfall: fall and spring maximums in the northern and central sectors and fall and winter maximums in the southern sector (AEMET, 2011). Fall and spring rains are mainly linked to cold-drop atmospheric situations. In the winter, Atlantic storms with a southern trajectory (Strait of Gibraltar) are frequent in the south of the Mediterranean coast of the Iberian Peninsula. In either of these two varieties, summer is always the season with the lowest rainfall contribution (Serrano-Notivoli et al., 2018; Mathbout et al., 2020; Sánchez-Almodóvar et al., 2022).

Because of the impacts of extreme hydrometeorological phenomena in the Mediterranean, such as droughts and floods, observation of their behavior in the recent past is justified. Previous work on the reconstruction of rainfall on a long timescale generally shows situations of rainfall shortage (Pauling et al., 2006; Camuffo et al., 2013; PAGES Hydro2k Consortium, 2017). The results obtained from instrumental data series highlight that rain shortages (droughts) are perceived at the seasonal level. The present work aims to analyze the most extreme phenomena detected in the aforementioned paper but using data that allow us to analyze rainfall deficits at the monthly level. Unfortunately, for the Iberian Peninsula as a whole there is only one instrumental data series in the study under review. For this reason, the instrumental data from the Barcelona station (1786–2022) complement the historical data from the MILLENIUM project ("European climate of the last millennium", project code IP 017008-2). The combination of instrumental and historical data has been used to study specific periods of anomalous temperature and rainfall conditions. One such widely studied case is the anomaly of the non-summer year of 1816, a consequence of the Tambora volcanic eruption (Trigo et al., 2009; Luterbacher and Pfister, 2015).

The Spanish Mediterranean basins are currently experiencing a severe rainfall shortage. Due to this serious situation, it is necessary to find references to droughts of equal or greater magnitude in order to understand the characteristics of these phenomena in their most extreme behavior. Studies carried out on the Iberian Peninsula to study historical droughts using historical data show significant results obtained from the use of rogations as a data (Domínguez-Castro et al., 2012; Tejedor et al., 2019). These studies make it possible to identify the importance of the 19th century for its study, highlighting specific years such as 1817 or 1824 (Domínguez-Castro et al., 2012). Despite these results, the data used in these studies were applied to yearly resolutions. The need for knowledge of past droughts adds to the need to expand the detail of existing studies on historical droughts in the study area.

Historical data allow us to observe the behavior of droughts in much more distant historical periods than those of the instrumental precipitation data series. Therefore, these data would allow us to improve the knowledge of drought natural variability over a longer timescale than the instrumental period. For periods where overlap exists, historical data (rogation ceremonies) can be correlated with early instrumental data. This aspect is novel and important for three main reasons, which motivate focusing this work on such analyses: (1) the existence of long instrumental records is scarce and spatially dispersed in Spain; (2) social changes during the 19th century make historical records of social impact based on rogations demonstrably inconsistent after 1836 (Gil-Guirado et al., 2016; Espín-Sánchez and Gil-Guirado, 2022), which discourages their use as proxies after this date; and (3) the available instrumental records and social impact data are contemporaneous.

For all of the reasons given above, in the current paper we will discuss the topic of the extreme droughts that affected the Mediterranean basins of the Iberian Peninsula during the early 19th century (1790–1830). Detailed study of drought events during this period is justified by the physical and social reasons that underline their exceptionality. The severity of the different droughts recorded, their cumulative duration and the impact they had on the societies of the Spanish Mediterranean basins do not have an equal magnitude in the recent collective memory. On the other hand, this period has been studied relatively well, thanks to climate reconstructions for the beginning of the 19th century based on natural and historical proxy data and the first instrumental meteorological data series (Prohom et al., 2016; Brönnimann et al., 2018b).

The novel aspect of the present study consists mainly in the fact that the period chosen (1790–1830) has not been analyzed in depth with historical data. Furthermore, it has not been analyzed with daily resolution data, as is the case in the present study. This paper focuses on the impacts caused by meteorological droughts because of the nature of the data used. The main sources of information used for the analysis of droughts in the historical period are the historical data of rogations (Spain, with a higher density for Catalonia) and the instrumental precipitation data sets of Barcelona (Catalonia, NE Spain). The case of the rogations differs from that of the instrumental series, since the latter focuses on the lack of precipitation, whereas the rogations would allow the analysis of agricultural drought (Brázdil et al., 2018). However, rogations also allow meteorological monitoring of the natural phenomenon, as the ceremonies themselves are interrupted when an improvement in rainfall is detected. This is because of the daily level of detail of the rogation system as a source of information (Martín-Vide and Barriendos, 1995). The very etymology of the rogations (pro pluvia, to obtain rain as usual) demonstrates the meteorological nature of the ceremony. Their purpose was not directly to obtain a large harvest but to achieve a good rainfall episode. The historical data at daily resolution used to carry out this study come from the AMARNA database on climate risks (Multidisciplinary Archives for the Analysis of Natural and Anthropogenic Risk – Arxius Multidisciplinars per a l'Anàlisi del Risc Natural i Antròpic in Catalan). This is a compilation effort focused on organizing climate information from historical proxies at high spatio-temporal resolutions. The total number of records for the period 1035–2022 CE amounts to slightly more than 19 000 cases, organized into more than 5500 episodes (Tuset et al., 2022). It is originally a database of torrential rainfall and flood events, and information on pluviometric deficits is also being introduced from the present study.

1.1 Research background

The early 19th century (1790–1830) is placed during the climate episode known as the Little Ice Age (hereafter, LIA) that occurred between the 14th and 19th centuries (Grove, 1988). This climate oscillation was clearly characterized by lower average temperatures with respect to the previous episode (Medieval Warm Period) and the subsequent episode (current global warming) (Fischer et al., 2007). Another significant aspect of the LIA is the irregular behavior of rainfall, with a clear increase in the frequency and magnitude of severe hydrometeorological events (Oliva et al., 2018; Barriendos et al., 2019; Gorostiza et al., 2021). In the case of the Iberian Peninsula, different oscillations were observed, including increases in heavy rains or droughts throughout this period (Barriendos, 1996). One of the most exceptional oscillations is called the Maldà Oscillation, which occurred between 1760 and 1800 (Barriendos and Llasat, 2003). The Maldà Oscillation was characterized by simultaneous increases in the frequency of heavy-rain events that alternated with drought periods. The alternation of extreme rainfall and drought events had a strong social and economic impact on the Iberian Peninsula. Specifically, the sequence of droughts, cold snaps and snowfalls had serious direct consequences on agriculture, while consecutive floods also damaged or destroyed a large amount of infrastructure. Furthermore, during the period of the Maldà Oscillation there was an emergence of uncommon epidemic diseases, such as smallpox or yellow fever viruses, occurring at the same time as more common diseases such as epidemic malaria or typhoid (Barriendos and Llasat, 2003; Alberola, 2010; Alberola and Arrioja, 2018).

Within the LIA, the early 19th century was characterized by an abnormally low amount of emitted solar radiation, which generated an overall decrease in the amount of solar radiation reaching Earth (Prohom et al., 2016). In addition to this external forcing factor, climate variability at the end of the LIA was also affected by several volcanic eruptions that occurred between 1790 and 1830 (a total of 302 eruptions with Volcanic Explosivity Index (hereafter, VEI) between 2 and 7) (Fang et al., 2023). Of these 302 eruptions, 247 had a VEI ≥ 2, 35 had a VEI ≥ 3, 16 had a VEI ≥ 4, 2 had a VEI ≥ 5, 1 had a VEI ≥ 6 and 1 had a VEI ≥ 7 (Global Volcanism Program, 2023). Among these volcanic eruptions, a sequence of large explosive volcanic eruptions stand out (Prohom, 2003; Wagner and Zorita, 2005; Lee and MacKenzie, 2010): unknown eruption (1808), Tambora (1815), Galunggung (1822) and Cosigüina (1835). Some studies indicate that the high-intensity volcanic eruptions, occurring between the LIA and the current global warming, led to a decrease in temperatures and an increase in rainfall irregularity in the study area (Gil-Guirado et al., 2021).

Among the three eruptions of the early 19th century, the 1815 Tambora eruption is considered one of the most significant of the past 2000 years in terms of the particles emitted (Raible et al., 2016). Also, it is considered to be the cause of the most pronounced climate anomaly of the first third of the 19th century (Brönnimann et al., 2018b). Due to its outstanding volcanic explosivity (VEI 7), this eruption was the largest and most devastating eruption recorded in the historical age and is considered to be responsible for the "year without a summer" of 1816 reported across Europe and North America (Trigo et al., 2009; Luterbacher and Pfister, 2015). This temperature anomaly severely affected central, western and northern Europe, with recorded temperatures between 2 to 3 °C below the average in areas of Spain and Portugal (Pfister and White, 2018). During that summer the number of rainy days almost doubled, while cloudy days were more frequent across Europe and North America. Alterations in the usual general atmospheric circulation pattern and its centers of action were also reported as a result of cooling due to the direct effect of the reflection of incident radiation associated with the presence of volcanic aerosols (Brönnimann et al., 2018b).

1.2 Historical drought studies in Spain

The analysis of historical droughts in Spain dates back to studies by Manuel Rico y Sinobas in the mid-19th century, in which he analyzed the impacts of drought episodes on agriculture. His main objective was to compile records in order to obtain a broad temporal dimension of the phenomenon (Rico y Sinobas, 1851). Subsequently, studies that were in some way related to drought events were carried out only sporadically until the beginning of the 1990s (Bentabol, 1900). One exception is the study by Couchoud (1965), who analyzed the region of Murcia in depth (SE Spain) based on a detailed compilation and analytical process. In 1994, two PhD theses on historical climatology that engaged with droughts were defended in Spain (Barriendos, 1994; Rodrigo, 1994). They constitute benchmark studies in the research on this topic. Since then there has been a proliferation of studies and publications in which drought is taken into consideration (see, among others, Rodrigo et al., 1994, 1995, 1998; Martín Vide and Barriendos, 1995; Barriendos, 1997; Barriendos and Martín-Vide, 1998), including manuals on natural risks (Olcina, 2001a). More recently, a new PhD thesis (Gil-Guirado, 2013) once again insisted on the need to study historical droughts in the Spanish Mediterranean basin based on a quantitative approach.

In addition to PhD theses, there are also recent publications focused on the study of historical droughts using a quantitative approach. An example that actually corresponds to the period analyzed in present work is a paper by Domínguez-Castro et al. (2012) that focused on droughts in the Iberian Peninsula (1750–1850). That article approaches the severe episodes of historical droughts by means of rogations at annual resolution. Other studies have continued this line of research in the Iberian Peninsula (Trigo et al., 2009; Fragoso et al., 2018; Tejedor et al., 2019; Bravo-Paredes et al., 2020) and have even gone into more detail for the Ebro basin (Cuadrat et al., 2022). The availability of pro pluvia rogations in the Hispanic cultural sphere extend beyond the Iberian Peninsula, as evidenced by works from Mexico and all Central American countries (Garza-Merodio, 2017; Alberola and Arrioja, 2018; Ramírez-Vega, 2021). Rogations are a liturgical mechanism that is also used in other Catholic countries, and therefore these studies can be extended to this broader religious sphere (Pfister, 2018; Garnier, 2019). Finally, the amount of information that is becoming available is already being organized into comprehensive databases such as AMARNA or in international initiatives (Domínguez-Castro et al., 2021).

Parallel to the research based on rogations, the study of historical droughts in the Iberian Peninsula has also been carried out through the analysis of historical instrumental precipitation data series (Prohom et al., 2016) or through the combination of data on rogations and precipitation series analyzed by means of drought indices (Tejedor et al., 2019). These studies allow us to observe severe droughts based on inter-annual variability.

1.3 Objectives

The main objective of this study is to analyze the patterns of drought episodes that affected the northeastern Iberian Peninsula during the early 19th century (1790–1830) using instrumental and historical sources. This period corresponds to the last stages of the Little Ice Age and was chosen due to severity of drought occurring in the Mediterranean basins of the Iberian Peninsula at that time. Additional objectives of this study are as follows. First, we seek to qualitatively and quantitatively extend the AMARNA database on climate risks to incorporate droughts and different social processes linked to environmental impacts in addition to hydrometeorological excesses (Tuset et al., 2022). Second, we compile and describe the variability of extreme hydrometeorological events (heavy rainfall and droughts) in the Spanish Mediterranean basin during the early 19th century in order to study how the opposite extreme events behave and interact with each other. We also seek to understand whether the behavior of past hydrometeorological extremes is similar to the modeled behavior for the future in the study area. In addition, the spatio-temporally coherent periods of climatic anomalies shown an increase in rainfall irregularity in the study area as part of their main characteristics (Gil-Guirado et al., 2016). Third, we characterize the drought episodes, analyzed from historical data, considering their duration, extension and severity at high resolution for the period analyzed. Finally, we analyze the entire instrumental precipitation data series of Barcelona (1786–2022) in order to characterize periods of drought.

In order to fulfill these objectives, the paper analyses the historical and instrumental data available in the Spanish Mediterranean basins using different timescales and spatial scales. The socio-environmental context during the early 19th century is analyzed using data compiled from historical documentary sources, namely the records of the pro pluvia rogation ceremonies held in the main villages of the affected regions. These data are compared with the analysis of the instrumental precipitation data series of Barcelona (1786–2022) based on different statistical techniques, including the use of the following three drought indexes: SPI (Standardized Precipitation Index) (McKee et al., 1993), SPEI (Standardized Precipitation Evapotranspiration Index) (Vicente-Serrano et al., 2010) and deciles (Gibbs and Maher, 1967).

The article focuses on analyzing climate variability during the early 19th century period and provides state-of-the-art results on droughts from a historical perspective in Spain and Europe as a whole. Subsequently, the results obtained are presented through graphical and cartographical resources.

2 Materials and methods

2.1 Sources of information

The sources of information used to analyze droughts in the early 19th century consist mainly of historical data and the Barcelona instrumental precipitation data series, which ranges from 1786 to 2022. The historical data on droughts in the Spanish Mediterranean basin during the early 19th century were obtained from documentary sources of public administrative and ecclesiastical institutions complied in the AMARNA database (Barriendos and Barriendos, 2021; Tuset et al., 2022). AMARNA is an archive that compiles historical climate episodes from different documentary sources that are then georeferenced and classified into numerical categories at a daily resolution. The information from AMARNA refers to any type of extreme meteorological event and its social impacts. Events about which there is more information are those relating to water excess (persistent rainfall, pluvial and fluvial floods) and rainfall deficits (droughts). The total number of records for the period 1035–2022 CE amounts to slightly more than 19 000 cases, organized into more than 5500 episodes (Tuset et al., 2022). Sources of information are mainly administrative and private documentary sources, with direct descriptions of events and their impacts. The institutional documentary sources also provide systematic and continuous records over time throughout the existence of the institution, with resources and conditions that favor the conservation of and access to the documents (Martín-Vide and Barriendos, 1995; Brönnimann et al., 2018a). Water deficits are obtained from the records of pro pluvia rogation ceremonies (cultural–historical proxy) from municipal and local ecclesiastical sources (Brázdil et al., 2018, 2019). Rogations are the main data proxy used in order to identify and compile information on droughts in the Spanish Mediterranean basin. The records of these ceremonies are generated and initiated by public authenticators in collegiate administrative bodies (municipal councils, cathedral councils), which guarantees the reliability of the document itself and the veracity of the information contained therein. The rogation records contain reliable and homogeneous information due to their institutional origin and the formal rigidity of the related liturgical procedures (Brázdil et al., 2018). The documentary record of the rogation ceremony informs us of the location, the date and duration of the drought conditions. With respect to the severity of the event, the application of a specific methodology based on the type of liturgical acts used enables their classification into categories and their numerical indexing (Martín-Vide and Barriendos, 1995; Barriendos, 1997). As a complement to these administrative sources, AMARNA also uses private personal sources, such as appointment books, memoirs or chronicles.

Rainfall excesses are also found in the same administrative documentary sources as the deficits, and their cataloguing and numerical classification procedure is also based on objective indicators. In the 1990s, simple and easy to cross reference classification criteria were proposed for all of the European basins based on the levels of river overflows and the damage recorded (Barriendos and Martín-Vide, 1998; Brázdil et al., 1999). The first studies that used these information sources in the area of study sought to conduct an overall reconstruction of the climate variability through the generation of weighted annual indices (Barriendos, 1996, 2005). Subsequent studies extended the analysis with annual indices for different locations of the Hispanic cultural sphere for both historical floods (Barriendos and Sánchez Rodrigo, 2006) and droughts (Domínguez-Castro et al., 2008, 2012; Rodrigo and Barriendos, 2008; Gil-Guirado et al., 2019; Tejedor et al., 2019).

In addition to the analysis of historical data, the second part of the study consists of statistical analysis of the instrumental precipitation data series of Barcelona spanning from 1786 to 2022. Unfortunately, the Barcelona series is the only continuous rainfall series available in the study area for the early 19th century. This information is scarce for such a large geographical area, but the Barcelona series is located in the area with the most historical information available for this period. Therefore, the joint analysis of instrumental and historical information is relatively consistent.

The Barcelona rainfall series used in this study comes mostly from the series elaborated by the Meteorological Service of Catalonia (Servei Meteorològic de Catalunya, SMC) (Prohom et al., 2016). This series ranges from 1786 to 2014 and was compiled from different institutional observers that generated records during the 18th and 19th centuries in the center of Barcelona (at around 30 m a.s.l.). For the 20th century the records were generated at the Fabra Observatory, placed outside of the city (on Mount Tibidabo at 412 m a.s.l.). The analysis of these sources has enabled the homogenization of the monthly precipitation data series from 1786 to 2014. For the period 2015–2022, we used rainfall series located in the city of Barcelona instead of continuing with the series from the Fabra Observatory for the following reasons: it corresponds to an altitude significantly different from that of the flat coastal area of Barcelona, it is placed far from the city center and it began its record measurements in 1913. Taking into consideration the high irregularity of the precipitation in the Mediterranean climate, these differences make it advisable to use a landmark closer to the historic center of the city of Barcelona. These considerations have been the subject of debate for years when defining climate instrument series for Barcelona (Prohom et al., 2016). To complete the SMC series up to the year 2021, instrumental records from a private observatory in the Can Bruixa neighborhood of Barcelona was used. In order to complete the remaining year, the series was completed with data from the official SMC Raval automatic station (University of Barcelona). These two series are validated by the SMC, and their data have been collected in the center of the city of Barcelona, making their values closer to those collected at the beginning of the series.

2.2 Indexing system for historical climate data

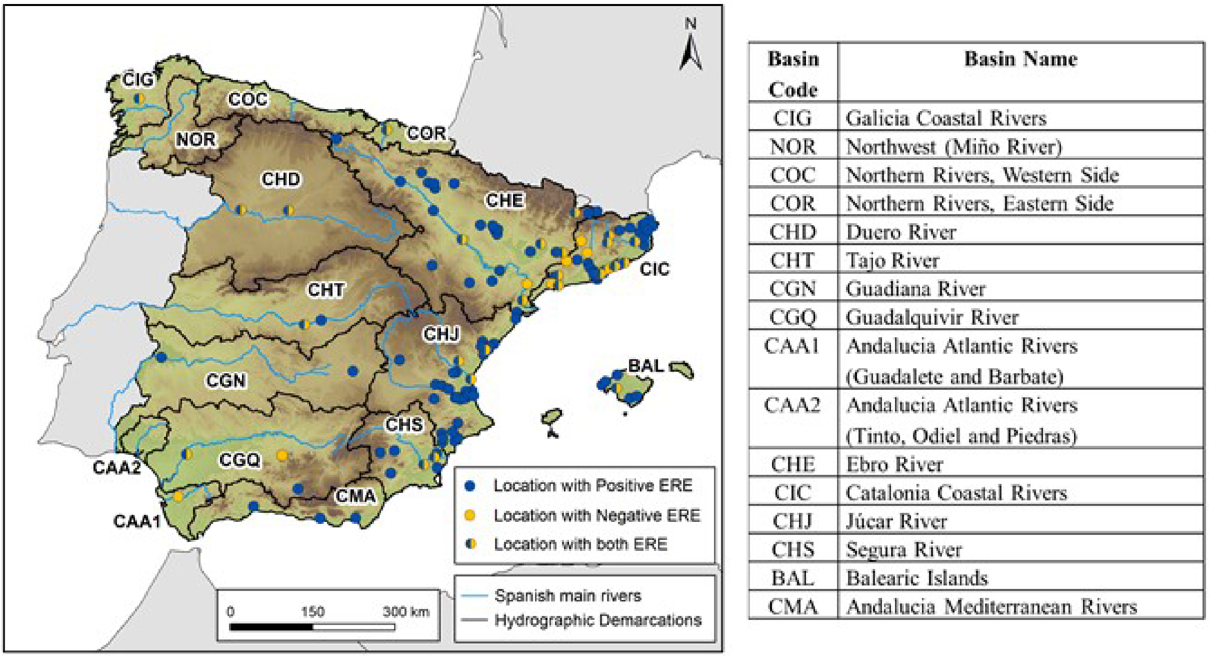
This study is based on the use of information on a daily scale drawn from the historical data obtained from the AMARNA database. This information is organized into cases and episodes. Every episode consists of a group of cases or records of different dates and locations that provide information about the impact and duration of each episode. Cases are the basic units of documentary record in which there is mention of some kind of impact on the water deficit. This can include decisions by the authorities to initiate or continue pro pluvia rogations, qualitative records of rainfall within a drought episode or records of the decisions taken by the authorities to end the rogations once the drought is considered to be over. The cases and episodes are classified into 5 categories and 15 sub-categories (Barriendos and Barriendos, 2021) (Table 1). These 15 thematic subdivisions correspond to the highest degree of detail observable in the documentary and bibliographic sources consulted (Table 1). For the specific case of drought (DR) episodes, these come mostly from records of the celebration of pro pluvia rogation ceremonies. These liturgical events, typical of the Catholic Church, are highly institutionalized. The adverse weather situation is detected by the monitoring and reports of the farming guilds. Their evaluations are assessed by the municipal councils which, in view of the severity of the situation, decide to hold the prayers. Finally, the ecclesiastical authorities are responsible for the effective execution of the ceremonies. This procedure has the positive factor of having administrative documentary sources generated by public administrations that guarantee the accuracy of the information, its objectivity and the reliability of its contents. It should be noted that the administrative documentation consulted is always validated by public authenticators (secretaries of municipal and ecclesiastical councils that are public notaries). These records provide information on both the duration and severity of drought events. From the documentation mechanism of the ceremonies, it is also possible to discern that the rogations present a formal differentiation in their liturgical acts according to the severity of the drought as determined by the specialized guild authorities. This liturgical format has remained almost unchanged since the Middle Ages, when continuous municipal and ecclesiastical records were already available. The difference between ceremonies is based on their format, with a total of five levels, always adapted to the cultural singularities of each town (e.g., Martín-Vide and Barriendos, 1995; Barriendos, 1997; Tejedor et al., 2019; Alcoforado et al., 2000; Gil-Guirado et al., 2019; Espín-Sánchez and Gil-Guirado, 2022), as follows: (1) simple prayers inside the churches; (2) prayers using the exhibition of relics or images inside the churches; (3) public processions through the public area of the town (planned routes through the main streets of the town); (4) until 1619, immersion of images or relics in water (from 1619 onwards, due to prohibition of immersions by the Vatican authorities, liturgical acts of similar solemnity were held in public spaces within the town's boundaries); and (5) pilgrimages to sanctuaries of special veneration that required a journey outside the town. By having the dates on which each ceremony is held, we can identify both the beginning and the end of the rogations, along with increases in severity. A level-1 rogation marks the beginning of each drought episode and a gratitude ceremony (Latin: *Te Deum Laudamus*) marks the end of the episode. Each drought episode will thus have a different duration, and its severity will be defined by the ceremonies between the first rogation and the closing of the ceremonies.

Table 1. Classification system of the AMARNA database (Barriendos and Barriendos, 2021).

Categories		Sub-categories	
Code	Name	Code	Name
ERE	Extraordinary rainfall event	FF PF PR SS DR	Fluvial flood Pluvial flood Persistent rainfall Sea storm Drought
ECE	Extraordinary convective event	HE ES WS	Hail event Electric storm Wind storm
ETE	Extraordinary thermic event	CW US HW	Cold wave Unusual snowfall Heat wave
SIE	Social impact event	EE PE FS	Epidemic event Plague event Food shortage
ERR	Technical mistake	ERR	Spurious case

The AMARNA database originally only provided data on water excesses recorded in historical periods for the Spanish Mediterranean basins (Tuset et al., 2022). An effort is currently being made to add data on droughts to the AMARNA database. In this regard, the period from 1790 to 1830 has been a test to see how the recently gathered data on droughts and the existing data on excess water fit together. Thus, the work proposed in this article supposed progressing from 0 cases and episodes of drought events for the early 19th century to the values with which the study has been carried out (2047 cases, of which 1132 cases correspond to drought events). The AMARNA database is still under development for other historical periods and is therefore not yet available for public access.

The georeferencing of all the historical data compiled in the AMARNA database allowed the use of Geographic Information System (GIS) tools for the cartographic representation of this historical information. The distribution of the droughts in the early 19th century has been represented both on a municipal level and with the cases grouped by hydro-



Basin Code	Basin Name
CIG	Galicia Coastal Rivers
NOR	Northwest (Miño River)
COC	Northern Rivers, Western Side
COR	Northern Rivers, Eastern Side
CHD	Duero River
CHT	Tajo River
CGN	Guadiana River
CGQ	Guadalquivir River
CAA1	Andalucia Atlantic Rivers (Guadalete and Barbate)
CAA2	Andalucia Atlantic Rivers (Tinto, Odiel and Piedras)
CHE	Ebro River
CIC	Catalonia Coastal Rivers
CHJ	Júcar River
CHS	Segura River
BAL	Balearic Islands
CMA	Andalucia Mediterranean Rivers

Figure 1. Spanish hydrographic basins analyzed in this study. Locations with historical information for the early 19th century. This specifies the locations that have records on positive ERE (FF, PF, PR and SS), negative ERE (DR) or both types of ERE.

graphic basin. These are the Spanish administrative units for managing water resources (Fig. 1) (MITECO, 2023). The organization at a municipal level allows for the analysis of the time–space distribution of the impacts caused by different drought episodes representative of the period of study. The different efforts to compile data on the AMARNA database on water excesses and droughts have resulted in a very characteristic distribution of data for the case of the early 19th century period (Fig. 1). Most of the points with information on water excesses collected in AMARNA are located in the Spanish Mediterranean basins. On the other hand, the information on droughts covers points all of Spain but has a higher density in the territory of Catalonia between the hydrographic basins of the Ebro (CHS) (Fig. 1). This disproportionate distribution in the amount of information between the Atlantic and Mediterranean basins is due to the effort being focused on the latter, where there is more interest in the study of hydrometeorological phenomena. Therefore, as the title of the paper indicates, the analysis of drought in the northeastern Iberian Peninsula uses information from the Atlantic basin of the Iberian Peninsula only as reinforcement or to complement better characterization of the episodes identified.

2.3 Generation of drought indices

Several drought indices were generated using the Barcelona precipitation data series (1786–2022). In all cases, the indexes were calculated based on monthly values and for groups of 12 months. Due to the irregular distribution of precipitation throughout the year in the northeastern Iberian Peninsula, the 12-month groupings are the ones that best group and detect drought episodes. Other groupings, such as 3 or 6 months, can detect a lack of precipitation that is typical of the usual conditions of the seasons and intra-annual variability (Gil-Guirado and Pérez-Morales, 2019). The SPI (Standardized Precipitation Index) (McKee et al., 1993) was the first index calculated and is widely used for classifying droughts (WMO and GWP, 2016). This index enables the analysis of the duration and variability of droughts and wet periods and is generated based on the transformation of the temporal precipitation data series in a standardized normal distribution (Lloyd-Hughes and Saunders, 2002; Zargar et al., 2011; Gil-Guirado and Pérez-Morales, 2019). The second index is the SPEI (Standardized Precipitation Evapotranspiration Index) (Vicente-Serrano et al., 2010), which is similar to the SPI but also uses the average monthly temperature variable (WMO and GWP, 2016). It is a relatively versatile index, it is simple to apply and it enables analyses to be carried out for any climate regime (Stagge et al., 2015). The third index used is the deciles index (Gibbs and Maher, 1967), which stands out for its applicability and simplicity and due to the calculations that it requires and the fact that it only requires precipitation data (Steinemann et al., 2005; Tsakiris et al., 2007). This method is obtained by dividing the distribution of the monthly precipitation data into deciles (WMO and GWP, 2016), which define thresholds for different water deficit conditions (Zargar et al., 2011; Eslamian et al., 2017).

The results obtained from the instrumental rainfall series of Barcelona (1786–2022) using the different indices (SPI, SPEI and deciles) have been statistically analyzed. Three different statistical tests have been carried out with the monthly rainfall series of Barcelona (Gil-Guirado and Pérez-Morales, 2019). On the one hand, the trends of the series have been calculated using the Mann–Kendall test. On the other hand, the Sen's slope has also been obtained. Finally, the breakpoints of the series have been analyzed using the Pettitt's test. In order to carry out these statistical tests, different scripts using the R language have been used, and these have been executed in RStudio to obtain the results.

Based on the results obtained from various drought indices, a detailed criterion has been established to classify the different drought episodes identified for the early 19th century. This criterion relies mainly on the SPI to define each episode based on the drought thresholds defined by the literature (McKee et al., 1993). Specifically, the start and end of a drought episode are determined by SPI values that cross the threshold of -0.70. This threshold is chosen to capture the transition between drought episodes and the transition periods into and out of drought conditions. A drought episode is characterized by having at least 5 consecutive months in which SPI values are consistently below -1.0, indicating moderate to severe drought conditions. By defining these specific ranges, we ensure a systematic and reproducible approach to identifying and analyzing drought episodes.

3 Results

3.1 Hydrometeorological extremes in Spain (1790–1830)

This study has found that the period (1790–1830) in which there is an accumulation of particularly severe drought episodes. This period coincides chronologically with the Dalton Solar Minimum and an anomaly in volcanic activity (eruptions of Tambora and other volcanoes mentioned). Obviously, the chronological coincidence does not presuppose any cause–effect relationship between the anomalies in solar and volcanic activity and the pluviometric anomalies under study.

The AMARNA database used in this paper provides a total of 19 115 cases spread over 5551 episodes for the period from 1035 to 2022. For the early 19th century (1790–1830), the AMARNA database provides 2047 cases for the whole of the Iberian Peninsula, which are grouped into 708 episodes (Barriendos et al., 2019). From the 2047 total cases, 1789 cases correspond to an ERE (extraordinary rainfall event). Within the ERE cases, there is a clear predominance of the subcategory DR (drought), with 64 % of the ERE cases (Table 2).

Table 2. Total number of cases of the five groups making up the ERE category (extreme rainfall event). The data are from the AMARNA database and have been elaborated upon by the authors.

Subcategories	Number of cases	Percentage
Fluvial flood (FF)	431	24.09 %
Pluvial flood (PF)	40	2.24 %
Persistent rainfall (PR)	164	9.17 %
Sea storm (SS)	22	1.23 %
Drought (DR)	1132	63.28 %
Total	1789	

The temporal distribution of the ERE episodes throughout the early 19th century reveals a predominance of droughts with respect to the other types of ERE but with a non-homogeneous distribution (Fig. 2). For instance, between 1790 and 1805 rainfall was abundant, meaning that floods were more significant than droughts in years such as 1793, 1797 or 1801 (Fig. 2). This decade also stands out due to its clear irregularity across different years, which could be related to the final part of an abnormal climate period detected between 1760 and 1800, known as the Maldà Oscillation (Barriendos and Llasat, 2003). The 5-year moving averages show the most pronounced episodes of droughts and water excesses during this period. Figure 2 highlights its temporal distribution: in the first decade, positive extreme peaks were interrupted with the drought of 1798. On the other hand, from the episode of 1807, droughts became predominant, being particularly severe between 1812 and 1825 (Fig. 2). The positive ERE cases diminished from 1806 definitively for the rest of the early 19th century, while the negative EREs increased from 1812. Between these two well-defined periods exists a transition period with a low number of heavy-rainfall or drought events.

The geographical distribution of ERE cases for this period also provides interesting information. It highlights the large number of cases recorded in the Spanish Mediterranean basin against those recorded in the Atlantic basins for the same period (Fig. 3). The Guadalquivir basin (CGQ) is the only Atlantic basin with an important amount of ERE cases. The predominance of drought in the Spanish Mediterranean basins contrasts with the greater impact of the positive ERE episodes in the Atlantic basins. In the Mediterranean area, the Júcar basin (CHJ) stands out as there is a high incidence of positive ERE, unlike the dynamics of the other Mediterranean basins. This bias can be applied to the CHJ, NOR, CGN and CMA (see Fig. 1) basins. For this reason, the majority of the information corresponds only to the episodes of positive ERE in the basins that suffer this bias.

The towns that account for more than 50 cases of drought were all spatially distributed across the Mediterranean basins, except for Seville, which is located in the Atlantic watershed (Fig. 4). Regarding the temporal distribution of drought at the different cities, the Murcia case is noteworthy due to its regularity of drought episodes compared

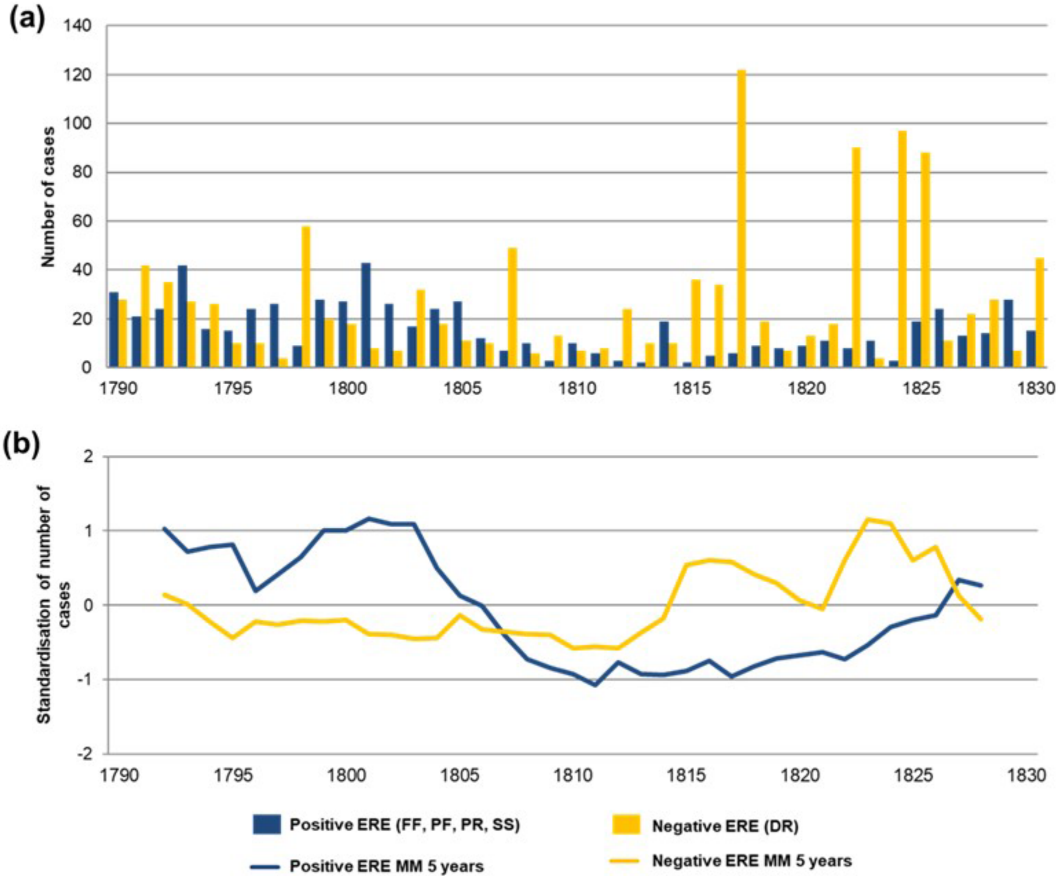


Figure 2. **(a)** Temporal distribution of positive EREs and negative EREs during the early 19th century (1790–1830). **(b)** The 5-year moving averages of the standardized values for the positive EREs and negative EREs. The data are from the AMARNA database and have been elaborated upon by the authors.

to the majority of the other cities that exhibit larger temporal variability (Olcina, 2001b). This fact is related to its geographical position in the southeast of Spain. Within this environment, "specific" drought events occur (the so-called "surestinas" or southeastern droughts) related to the lack of precipitation from the Atlantic and absence of Mediterranean rainfall events (Olcina, 2001b).

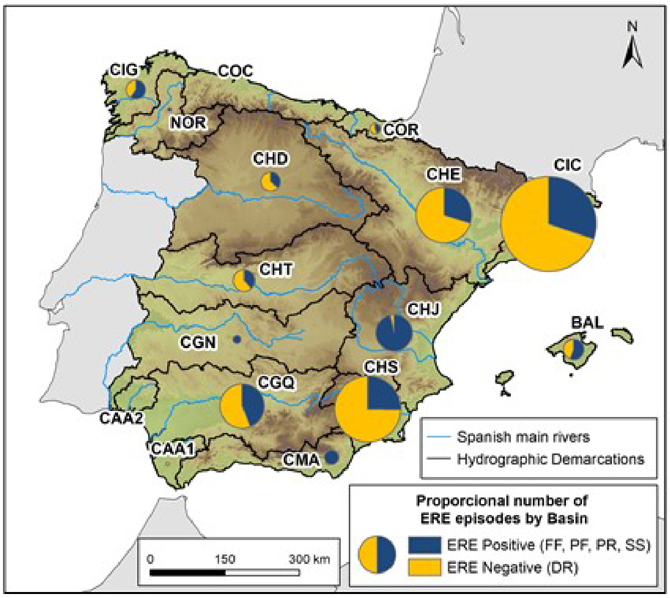
3.2 Drought analysis of the early 19th century in the Spanish Mediterranean basin

Table 3 shows historical data from the most severe drought episodes of the early 19th century based on all the cases from all the Spanish towns that record rogation ceremonies for each drought episode. In this regard, it will be possible to consider the different nuances that appear in the most representative droughts of the analyzed period.

Table 3. Summary of the severe drought episodes according to historical data for the early 19th century. The data are from the AMARNA database and have been elaborated upon by the authors.

Episode	Year of greatest impact (no. of cases)	Approximate duration	Total cases
1798–1799	1798 (58)	25 months	78 cases
1807–1808	1807 (49)	19 months	55 cases
1812–1814	1812 (24)	21 months	44 cases
1816–1818	1817 (122)	37 months	175 cases
1822–1825	1824 (97)	40 months	279 cases

The first of these episodes runs from December 1797 to December 1799, with the peak in intensity being in March and April 1798. This episode stands out as it occurred several years before the megadrought of 1812–1825 and was possibly an episode still linked to the Maldà Oscillation (Barriendos and Llasat, 2003). It affected five hydrographic basins (Catalan, Ebro, Segura, Tagus and Guadalquivir), three of which are Mediterranean basins (Fig. 5). Despite its considerable extension, this episode had a limited duration, with only a few months of rogations. The exception is the municipality of Murcia, where rogations were recorded for 10 of the 25 months that the episode lasted. Furthermore, this



Basin Code	Positive ERE (Nr)	Negative ERE (Nr)
CIG	18	12
NOR	1	0
COC	0	0
COR	4	5
CHD	11	19
CHT	15	24
CGN	5	0
CAA1	0	1
CAA2	0	0
CGQ	71	90
CMA	17	0
CHS	90	265
CHJ	104	4
CHE	75	177
CIC	223	518
BAL	19	15
Total	**653**	**1130**

Figure 3. Number of positive ERE cases (FF, PF, PR, SS) and negative ERE cases (DR) for the different Spanish river basins during the early 19th century (1790–1830). A list explaining the basin codes can be found in Fig. 1. The data are from the AMARNA database and have been elaborated upon by the authors.

episode was noteworthy in this town due to plague outbreaks (Zamora Pastor, 2002).

The second episode of severe drought occurred between January 1807 and July 1808 (Fig. 5), with the largest number of cities holding rogations in October 1807. It affected six river basins (Catalan, Ebro, Balearic, Segura, Duero and Guadalquivir), four of which are Mediterranean basins. Its main characteristic is that it had a greater impact on towns in the southern sector of the Atlantic and Mediterranean watersheds of the Iberian Peninsula, such as Murcia and Seville.

The third episode accumulated less cases of drought but marked the beginning of the megadrought that lasted until 1825, with different regional effects throughout the sequence. It occurred between March 1812 and April 1814 with the peak in severity being in April 1812 (Fig. 5). Despite the low number of rogations recorded (44), significant effects on crops were documented, causing wheat shortages and widespread famine in the Mediterranean basins. It had a broad impact across the Iberian Peninsula, affecting eight river basins (Catalan, Ebro, Balearic, Júcar, Segura, Duero, Tagus and Guadalquivir), three of which are in the Atlantic watershed.

The fourth episode runs between December 1815 and November 1818 (Fig. 5) and stands out for the impact of the drought during 1817, which was very severe in Catalonia, with instrumental records in Barcelona that were unprecedented until that point (Moruno, 2021). In this episode, there was an exceptionally dry month (April 1817) in which 14 of the 20 municipalities recorded pro pluvia rogations. This drought affected eight very broadly distributed river basins: four Mediterranean basins (Catalan, Ebro, Balearic and Segura) and four Atlantic basins (Galician, Duero, Tagus and Guadalquivir). Rogations were made during this drought for many months, particularly in the cities of Murcia and Girona, with 12 and 11 months, respectively.

The last episode took place between January 1822 and January 1826 (Fig. 5), although the year 1823 recorded a low number of rogations. This drought is noteworthy for being the longest and most persistent of the early 19th century (40 months). Three different peaks of severity can be observed: March 1822, April–May 1824 and February 1825. This drought affected eight very broadly distributed river basins: four Mediterranean basins (Catalan, Ebro, Balearic and Segura) and four Atlantic basins (Galician, Duero, Tagus and Guadalquivir). Also significant was the large accumulation of rogations carried out each month in the towns affected. For example, the town of Vic recorded 20 months of rogations, Murcia 17 months and Barcelona 15 months. This episode was accompanied by price increases of wheat and the emergence of a locust plague that affected different towns (Azcárate, 1996).

3.3 Analysis of the instrumental precipitation data series of Barcelona (1786–2022)

The analysis of the instrumental precipitation data series of Barcelona (1786–2022) was developed using three different drought indices (SPI, SPEI and deciles) (Fig. 6). The three drought indices reported a significant number of extreme drought events, in terms of both severity and duration, dur-

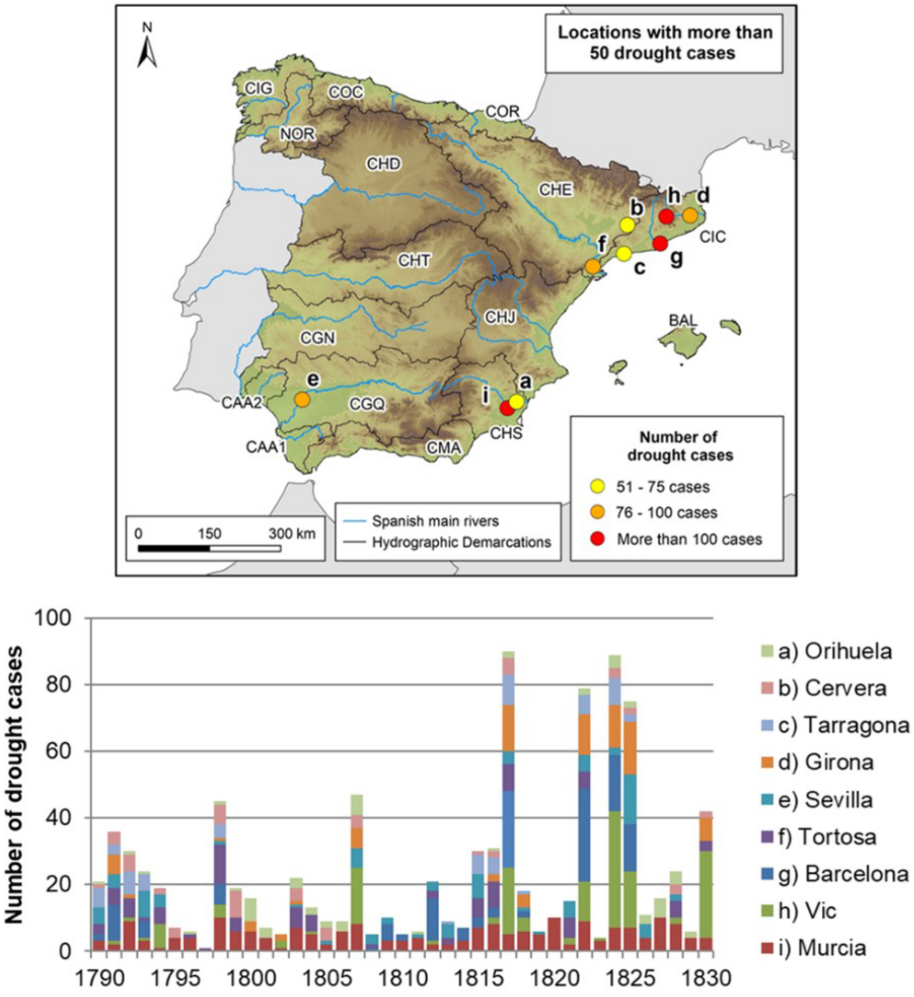


Figure 4. Towns with more than 50 cases of drought during the early 19th century. The data are from the AMARNA database and have been elaborated upon by the authors.

ing the early 19th century. A dry period between 1812 and 1825 stands out for its significant severity and duration. The three drought records also show values of relative abundant rainfall from the end of the 19th century until the end of the 20th century. The beginning of the 21st century reveals an upturn in the severity and duration of drought episodes with respect to the 20th century. This dry period that continues to the present day appears to be less intense than those of the early 19th century but may eventually become of similar duration and severity.

The SPI, in comparison with the behavior of the other two indices, more clearly highlights the peaks of greater severity, both positive and negative (Fig. 6). In this regard, 1817 stands out as the driest year in the precipitation data series, with months of maximum severity reaching values close to −4 (−3.91 in the month of August) (Table 5). If we look at the results of this index, it becomes clear that after the early 19th century, during the 1830s, the years in drought conditions were prolonged, ending around 1840. From the mid-19th century, a new phase began with a low occurrence of prolonged dry periods until the end of the 20th century. In the 21st century, severe drought values can be observed again. For example, in 2021, a negative value of the SPI of close to −3 was recorded for the first time since the early 19th century. The SPEI shows a different result to the other two indices as it combines rainfall and temperature values. In this respect, it is noteworthy that the most severe year of the series according to the SPEI was not 1817 but 1822. It is possible that the negative thermal effect of the Tambora eruption (1815) was still significant in 1817, resulting in 1822 having a higher temperature and consequently a lower SPEI value. The 1870–1890 drought episode, which does not stand out so much in the other two indices, is also perceived as severe. For the 20th century, SPEI shows a phase of positive values that lasted 20 years from the 1970s to the 1990s with almost no months with negative values. In contrast, for the beginning of the 21st century there are hardly any years with such positive values (Fig. 6). Undoubtedly, the recent ther-

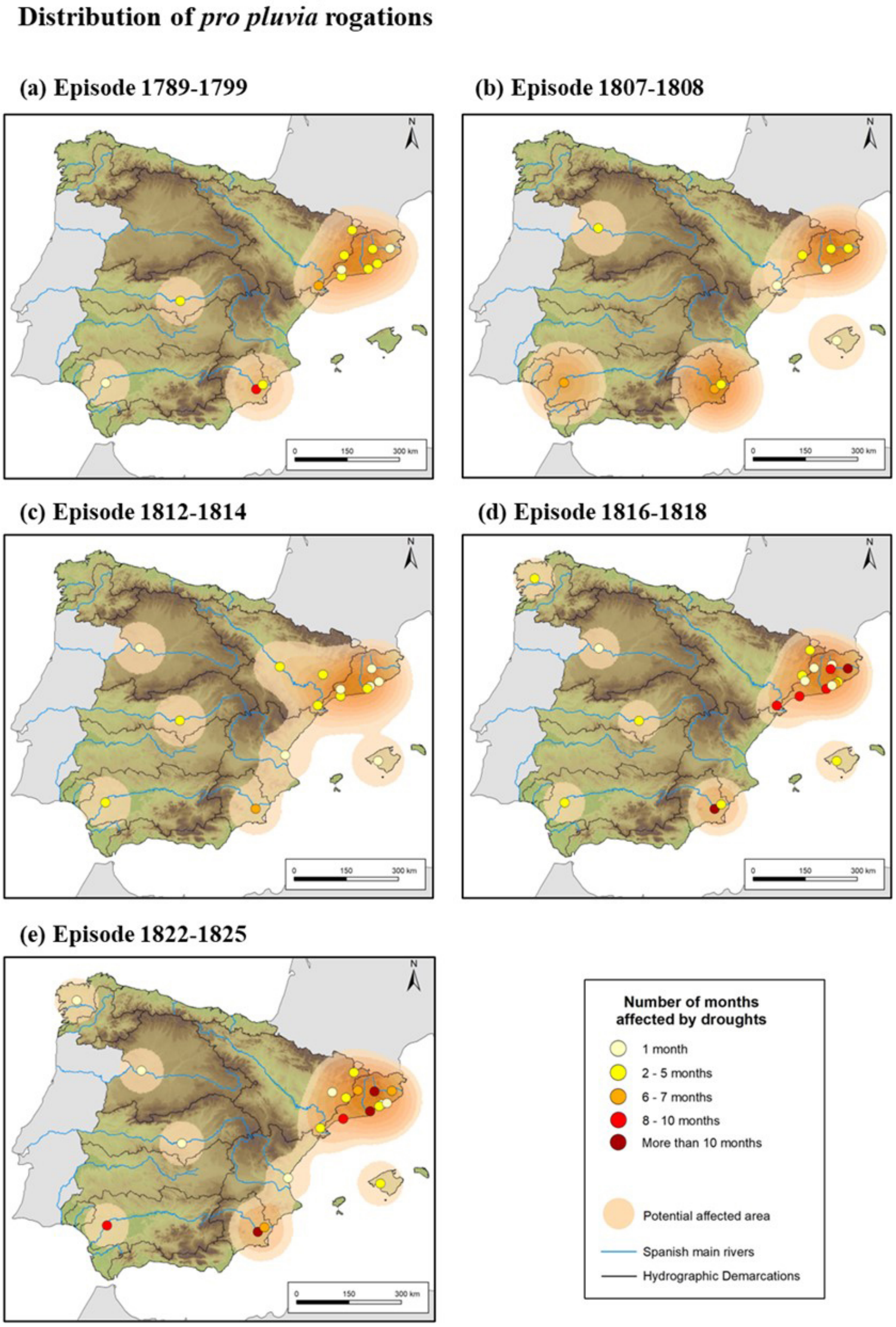


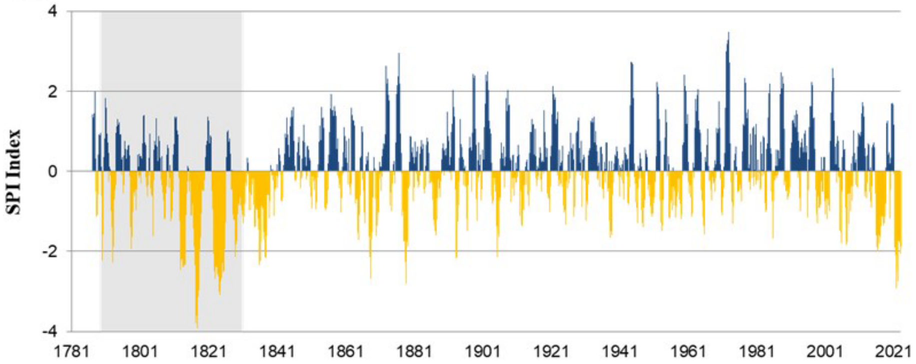
Figure 5. Distribution of pro pluvia rogations by municipality. **(a)** Drought episode of 1798–1799. **(b)** Drought episode of 1807–1808. **(c)** Drought episode of 1812–1814. **(d)** Drought episode of 1816–1818. **(e)** Drought episode of 1822–1825. The data are from the AMARNA database using ArcMap GIS software and applying the kernel density tool.

mal warming increases the intensity of negative SPEI values and presents increased problems for water management.

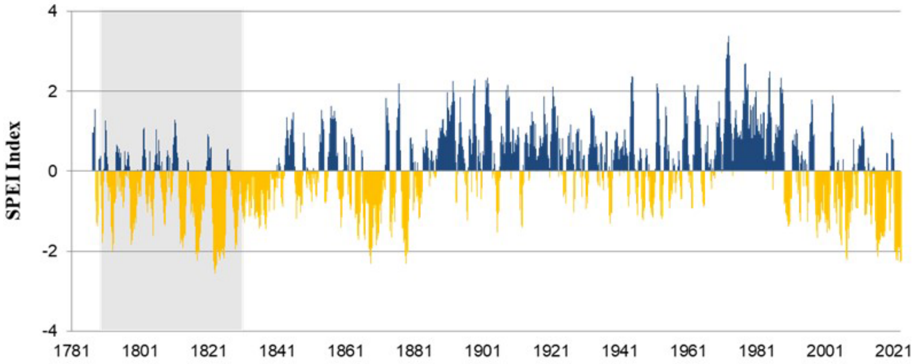
The behavior of the deciles index is very similar to that obtained with the SPI index. This index softens the extreme positive and negative behaviors. Thus, the interpretation of rainfall abnormalities does not help, with only the most evident episodes being highlighted.

The results obtained with the Pettitt test are very similar for the SPI and decile index values, although there are differences with respect to the SPEI index (Table 4). The main difference is the position of the first breakpoint, which for the case of the SPI and deciles occurred right at the end of the early 19th century in the 1840s. On the other hand, for the SPEI index, this first breakpoint occurred at the end of the

(a) SPI – 12 months



(b) SPEI – 12 months



(c) Deciles – 12 months

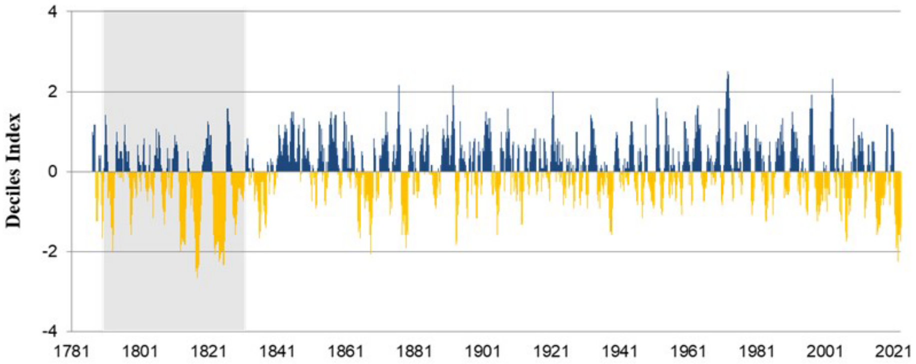


Figure 6. Monthly values of the SPI, SPEI and deciles indices for the instrumental precipitation data series of Barcelona (1786–2022). The study period has been shaded in grey. The data are from Prohom et al. (2016) and have been elaborated upon by the authors.

19th century, when a strong dry period that had lasted from 1860 to 1880 ended and is much more important in this index than in the other two analyzed. With respect to the breakpoint that marks the end of the wet period of the 20th century, the SPI and deciles indices coincide with the same period at the end of 1997. Meanwhile, the SPEI marks it at the end of the 1980s, after the wet phase of the 1970s and 1980s. From this point, the three indices go back to indicating negative averages for their respective series (Table 4).

Based on the values of the three indices, the drought episodes are summarized for the Barcelona data series (Table 5). It reveals a greater number of drought episodes recorded in the 19th century compared to the 20th century, in which droughts were not only scarce but also shorter and less severe (Fig. 7). This can be confirmed if we consider that droughts are more frequent and severe in the first 20 years of the 21st century than during the 20th century.

The droughts of the early 19th century (nos. 2 to 9), particularly those in the middle part of the period, stand out due

Table 4. Results of the breakpoint analysis carried out by means of the Pettitt Test on the three drought indices used in this study (SPI, SPEI and deciles). The table describes the date (month and year) on which the first and second breakpoints occur. There are also three more columns indicating the average of the index values between breakpoints, the number of months and the number of years. The data are from Prohom et al. (2016) and have been elaborated upon by the authors.

Monthly data series	First section's average	First break. point	Second section's average	Second break. point	Third section's average
SPI	−0.48 (669 months, 56 years)	Oct 1842	0.21 (1862 months, 155 years)	Dec 1997	−0.22 (301 months, 25 years)
SPEI	−0.43 (1157 months, 96 years)	Jun 1883	0.56 (1266 months, 105 years)	Dec 1988	−0.52 (409 months, 34 years)
Deciles	−0.34 (643 months, 54 years)	Aug 1840	0.15 (1886 months, 157 years)	Oct 1997	−0.25 (303 months, 25 years)

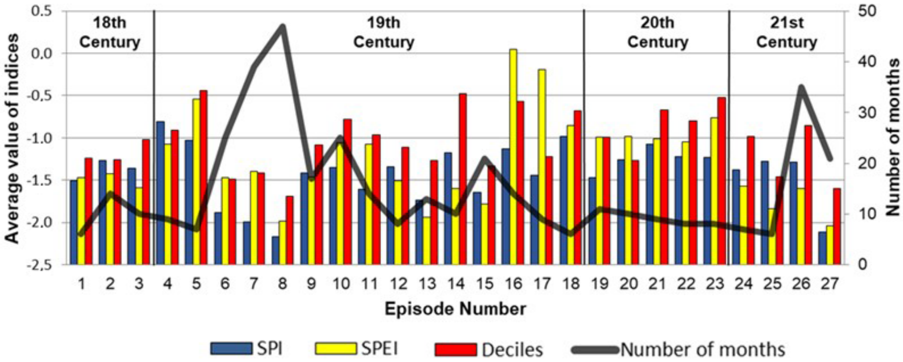


Figure 7. Representation of the mean values of the indices and the duration in months of the drought episodes described in Table 5. The data are from Prohom et al. (2016) and have been elaborated upon by the authors.

to their extreme severity, when the droughts were severe and a large number of dry months were concentrated in a short period of time (Table 5, Fig. 7). For the rest of the drought episodes of the series, we can observe that the majority had a shorter duration (Fig. 7). According to the average value of indices and the number of dry months, only three noteworthy drought episodes are outside of the early 19th century: 1877–1879 (no. 15), 2015–2018 (no. 26) and 2021–2022 (no. 27).

4 Discussion

The comparison between the results obtained from the historical data and the instrumental data series is part of the main objective of this study. This comparison makes it possible to contrast the reliability of the methods used and assess the consistency of the results obtained.

The combination of different proxy data expands our knowledge of the extreme hydrometeorological events, whether they be excesses or deficits, occurring in the past. In this case, the historical data and the instrumental data series of Barcelona have allowed us to analyze one of the driest known periods in the study area (Table 6). The comparison of the standardized values of the historical series with the instrumental indices enables us to observe the synchrony between the historical proxy and the instrumental data (Fig. 8). The coincidence of the duration of the episodes from the historical data and instrumental series is noteworthy. The only episode for which the durations are different is that of 1807, attributable to the fact that it mainly affected the southern regions of the Iberian Peninsula (and for longer periods). In terms of the severity of the episodes, the coincidence between the two series of data is also noteworthy, with the episodes with the most documented cases coinciding with those with a lower SPI index. The only episode that does not follow this pattern is that of 1812, in which the number of negative ERE cases is relatively low. However, on the other hand, according to the SPI it is the episode with the third-lowest mean of the early 19th century (1790–1830). The use of elements related to the social vulnerability to drought and extending the length of the data collection in different locations would help to resolve these specific uncertainties and constitute lines of research to be developed in the future.

Figure 8 shows the coincidence of the droughts according to the historical data (positive values) with the negative oscillations shown by the SPI and SPEI indices. The overlapping

Table 5. Drought episodes in the instrumental precipitation data series of Barcelona (1786–2022).

Episode no.	Date: Onset	Date: Ending	Month no.[a]	Averages of index values for each episode: SPI	SPEI	Dec.	Minimum values of the episodes[b]: SPI	SPEI	Dec.	Month
1	Sep 1789	Feb 1790	6	−1.51	−1.47	−1.24	−2.22	−1.79	−1.67	Nov 1789
2	May 1792	Jun 1793	14	−1.27	−1.42	−1.26	−2.29	−2.00	−2.00	Jan 1793
3	Mar 1798	Dec 1798	10	−1.36	−1.59	−1.02	−1.94	−1.76	−1.58	May 1798
4[c]	Sep 1807	May 1808	9	−0.81	−1.07	−0.91	−1.19	−1.31	−1.33	Jan 1808
5	Oct 1809	Apr 1810	7	−1.03	−0.54	−0.44	−1.25	−0.74	−0.67	Dec 1809
6	May 1812	May 1814	25	−1.88	−1.47	−1.49	−2.46	−1.82	−2.00	Oct 1812
7	Sep 1815	Nov 1818	39	−1.99	−1.40	−1.41	−3.91	−2.24	−2.67	Aug 1817
8	Jan 1822	Nov 1825	47	−2.17	−1.98	−1.69	−3.10	−2.22	−2.17	Jan 1824
9	Jan 1828	May 1829	17	−1.41	−1.46	−1.08	−2.14	−1.95	−1.58	Oct 1828
10	Apr 1834	Apr 1836	25	−1.35	−1.06	−0.78	−2.35	−1.44	−1.67	Nov 1835
11	Nov 1836	Dec 1837	14	−1.61	−1.07	−0.96	−2.17	−1.46	−1.42	Aug 1837
12	Apr 1864	Nov 1864	8	−1.34	−1.51	−1.11	−1.71	−1.72	−1.50	Sep 1864
13	Oct 1867	Oct 1868	13	−1.74	−1.94	−1.27	−2.69	−2.32	−2.08	Mar 1868
14	Oct 1869	Jul 1870	10	−1.18	−1.60	−0.48	−1.62	−1.86	−0.75	Nov 1869
15	May 1877	Jan 1879	21	−1.64	−1.78	−1.33	−2.80	−2.31	−1.92	Aug 1978
16	Jul 1886	Aug 1887	14	−1.13	0.05	−0.57	−1.60	−0.16	−0.92	Mar 1887
17	Feb 1893	Oct 1893	9	−1.44	−0.19	−1.22	−2.19	−0.79	−1.83	Apr 1893
18[c]	Feb 1896	Jul 1896	6	−0.98	−0.85	−0.68	−1.49	−1.22	−1.17	Jun 1896
19	Dec 1904	Oct 1905	11	−1.47	−0.99	−0.99	−2.15	−1.53	−1.58	Apr 1905
20	Nov 1937	Aug 1938	10	−1.26	−0.98	−1.27	−1.65	1.32	−1.50	Mar 1938
21	May 1947	Jan 1948	9	−1.07	−1.01	−0.67	−1.40	−1.23	−0.83	Oct 1947
22	Oct 1952	May 1953	8	−1.22	−1.05	−0.8	−1.49	−1.20	−1.00	Mar 1953
23	Feb 1965	Sep 1965	8	−1.23	−0.76	−0.52	−1.58	−0.88	−0.75	Sep 1965
24	Mar 2005	Sep 2005	7	−1.38	−1.57	−0.98	−1.79	−1.86	−1.25	Jul 2005
25	Nov 2006	Apr 2007	6	−1.28	−1.84	−1.46	−1.84	−2.15	−1.75	Jan 2007
26	Sep 2015	Jul 2018	35	−1.29	−1.60	−0.85	−2.00	−2.15	−1.50	Mar 2016
27	Apr 2021	Dec 2022	21	−2.11	−2.04	−1.6	−2.92	−2.22	−1.92	Sep 2021

[a] Number of months is determined by the following criteria: episodes must have at least 5 months below a −1 value in the SPI. The count of months will start and finish with the values below −0.70. [b] The month with the lowest value of each episode corresponds to the SPI. The data are from Prohom et al. (2016) and have been elaborated upon by the authors. [c] The episodes of 1807–1808 and 1896 have fewer than 5 months below −1 but their importance makes it interesting to mention them.

Table 6. Characteristics of the five principal drought episodes of the early 19th century (1790–1830) according to historical data and instrumental series. The data are from Prohom et al. (2016) and the AMARNA database and have been elaborated upon by the authors.

Episode no.	Date according to historical data: Onset	Ending	Month no. hist. data	ERE DR no. of cases	Date according to instrumental data: Onset	Ending	Month no. inst. data	SPI episode average
3	Dec 1797	Dec 1799	25	78	Mar 1798	Dec 1798	10	−1.36
4	Jan 1807	Jul 1808	19	55	Sep 1807	May 1808	9	−0.81
6	Mar 1812	Apr 1814	26	44	May 1812	May 1814	25	−1.88
7	Dec 1815	Nov 1818	36	175	Sep 1815	Nov 1818	39	−1.99
8	Jan 1822	Jan 1826	49	279	Jan 1822	Nov 1825	47	−2.17

of this information highlights the importance of the droughts in the final part of the early 19th century, specifically between 1815 and 1825, although the instrumental data indicate that this period could have started in 1812. For this reason, it is desirable to analyze the three drought episodes in which there is a high degree of alignment between the instrumental data the historical proxy data in more detail.

- The drought of 1798 stands out as it forms part of the rainfall irregularity typical of the Maldà Oscillation (Barriendos and Llasat, 2003). This drought occurred between two phases of intense rainfall. The alternation of floods or heavy rains with droughts is typical in areas with a Mediterranean climate. Despite this fact, this is the only drought of the early 19th century that precedes

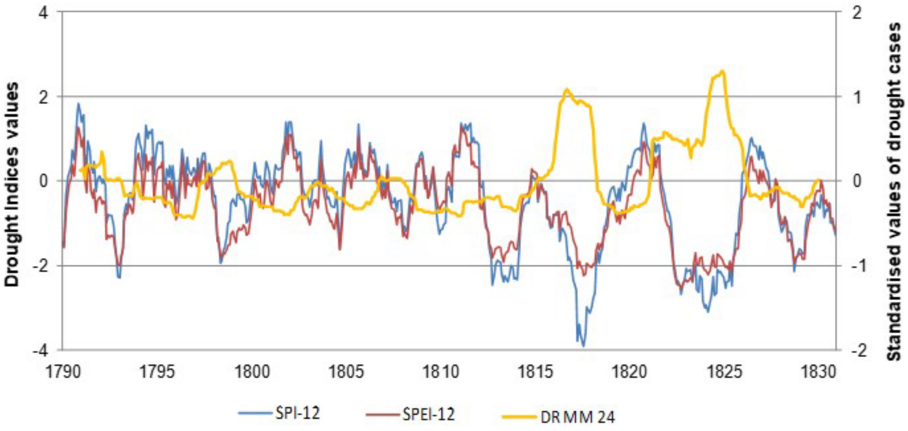


Figure 8. Comparison of the results of the drought indices (SPI and SPEI) and the 2-year moving average of the standardized monthly values of the drought cases (DR). The data are from Prohom et al. (2016) and the AMARNA database and have been elaborated upon by the authors.

and is preceded by flood or heavy-rain episodes in the northeastern Iberian Peninsula.

- The drought of 1817 differs from others in the early 19th century as it is the single year with the lowest value according to the SPI index and also the year with the most drought cases registered in the AMARNA database (120). Despite this strong impact, mainly corresponding to the first half of 1817, the episode was not as long as that of 1822–1825, and for this reason it was less severe than this latter episode according to the SPEI index.
- The drought of 1822–1825 stands out for its duration of around 40 months according to the rogations and 46 months according to the instrumental series. This makes it the longest episode not only of the early 19th century but also of the whole precipitation series of Barcelona (Table 6). Moreover, this episode is the one with the highest severity in terms of both the accumulation of drought cases (279) and the SPI average for the episode as a whole. It is also worth mentioning that this episode is the most severe of the entire Barcelona rainfall data series according to the SPEI index.

Based on the standardized data series of the number of droughts for the early 19th century, the correlation coefficient has been calculated with the values of the different drought indices with which the precipitation sets of Barcelona have been analyzed (Table 7). To correlate our drought index with the SPI, SPEI and deciles values, we performed different correlation tests with RStudio software (Posit team, 2024) taking into account the normality or non-normality of the data. In this regard, the results of the Shapiro–Wilk test show that the SPI and deciles series do not deviate significantly from normality (p value > 0.05). However, the SPEI series and our drought index show significant deviations from normality ($p < 0.05$). Given these results, we opted to apply different correlation methods: Pearson's correlation for normally distributed data and Spearman's and Kendall's correlations for data that did not meet the assumption of normality. Correlation analyses show moderate to weak negative correlations in all cases. In Pearson's correlation, correlation coefficients range from -0.59 to -0.65, with coefficients of determination (R^2) indicating that between 35 % and 42 % of the variability in the drought indices can be explained by our index. Spearman and Kendall correlations, which do not assume normality of the data, show lower coefficients, suggesting weaker correlations, with R^2 values ranging between 0.08 and 0.22. However, given the specific nature and context of our index, it can be considered a suitable proxy for drought, especially when used in combination with other indices and methods of analysis.

The study of extreme drought episodes in the past is important for understanding the pattern of low-frequency episodes and for addressing the droughts occurring in the context of climate change, which have erratic behavior according to the most recent models (IPCC, 2023). Furthermore, the knowledge generated for the study over a long period of time also enables us to better understand the vulnerability of society in different historical contexts and the way in which it has adapted over time to droughts.

Different studies carried out on droughts for the whole of the Mediterranean region for long time periods (Marcos-Garcia et al., 2017; Xoplaki et al., 2018; Kim and Raible, 2021) reveal that it is one of the most vulnerable regions to this natural risk within the context of global warming. Taking into account the results of this study, the importance of droughts in the Mediterranean region is underlined. Given its importance in the current context, it is necessary to analyze droughts with the support of different drought indices and other climatic indicators to determine their severity (Kim and Raible, 2021). The availability of early instrumental data series is highly important for finding a wider range of drought severities and typologies than those found only by analyzing

Table 7. Pearson, Spearman and Kendall correlation and determination coefficients of drought index values and historical data.

Index	Pearson correlation		Spearman correlation		Kendall correlation	
	Correlation coefficient (R)	Coefficient of determination (R^2)	Correlation coefficient (R)	Coefficient of determination (R^2)	Correlation coefficient (R)	Coefficient of determination (R^2)
SPI	−0.62	0.38	−0.39	0.15	−0.28	0.08
SPEI	−0.59	0.59	−0.44	0.19	−0.31	0.1
Deciles	−0.65	0.42	−0.47	0.22	−0.35	0.12

the 20th century. This relationship is shown in the research carried out by Erfurt et al. (2020), which combines historical instrumental data with dendrochronological records to analyze the period of the beginning of the 19th century in southeastern Germany. With respect to the use of dendrochronological data to analyze the droughts and megadroughts of the past, the Old-World Drought Atlas is also worth mentioning (Cook et al., 2015). This publication includes a severe drought that occurred at the beginning of the 19th century between the Little Ice Age and the modern climate period.

Other authors, particularly in the study of the Iberian Peninsula, have used historical data for classifying droughts in the period at the beginning of the 19th century (Domínguez-Castro et al., 2012; Gil-Guirado et al., 2019; Gil-Guirado and Pérez-Morales, 2019). It is worth highlighting the article by Domínguez-Castro et al. (2012) in which the historical data are combined with instrumental data to characterize the droughts of the period analyzed in Spain. In this case, the same dry periods of great intensity are detected (1817 and 1824) by both the historical and the instrumental data series. The authors conclude that the relationship between these droughts and external forcing factors is clear, but more research is also required to confirm this conclusion.

Furthermore, the modeling used by Kim and Raible (2021) does not show any extraordinary occurrence of droughts for the Mediterranean region as a whole during the early 19th century. These authors also do not relate rainfall patterns with the volcanic eruptions emitting more particles into the lower stratosphere, such as Tambora. According to their study, droughts occurring in the Mediterranean are mainly due to the internal dynamics of the climate system and not external forcing factors (intertropical volcanic eruptions and solar radiation variations) (Kim and Raible, 2021). The same conclusion has been obtained for the eastern Mediterranean region, albeit for a different period than the one studied in this research (Xoplaki et al., 2018). For these reasons, it may be concluded that the relationship between the external forcing factors can lead to different rainfall patterns depending on the region in which specific conditions prevail.

In the case of the Iberian Peninsula, the combination of intertropical volcanic eruptions with positive phases of the North Atlantic Oscillation during the first 2 years after the eruption could result in dry periods for the Iberian Peninsula and wet phases for central Europe (Domínguez-Castro et al., 2012). In addition, the lack of droughts detected in southeastern Germany during the early 19th century could reinforce this hypothesis (Erfurt et al., 2020). In this study of droughts in southeastern Germany, despite the lack of droughts in the early 19th century, there were temporal coincidences with other severe drought episodes, such as those occurring at the end of the 19th century (between 1857 and 1870) and at the beginning of the 21st century (2003 to 2018) (Erfurt et al., 2020). This period coincides with two of the most severe drought episodes of the 21st century according to the records of the instrumental precipitation data series of Barcelona: the droughts of 2007–2008 and 2015—18 (see Table 5).

5 Conclusions

The results obtained with this broad-timescale research contribute to a better understanding of drought episodes occurring in the early 21st century in the study area. Data collection and the extension of databases allow for a substantial improvement in our knowledge of drought patterns in the study area.

This study has found a time period in which there is an accumulation of particularly severe drought episodes (1812–1825). This period coincides chronologically with the Dalton Solar Minimum and an anomaly in volcanic activity (eruptions of Tambora and other volcanoes). Obviously, the chronological coincidence does not presuppose any cause–effect relationship between the anomalies in solar and volcanic activity and the pluviometric anomalies under study.

One of the main results achieved in this research is the high negative correlation between the drought historical data and the instrumental precipitation data sets of Barcelona. This correlation validates the historical information for the study of climate droughts from a historical perspective. Despite their different origins and methodologies, these two data sources have shown that they can provide information that is comparable, enabling the reinforcement of the importance of the episode recorded (floods or droughts).

The combined use of instrumental and historical sources shows changes in rainfall variability in specific periods, alternating between periods of heavy rainfall and drought. Accordingly, in the Spanish Mediterranean basins during the early 19th century, between 1810 and 1830, the alternation between periods of heavy rainfall and drought is revealed. In contrast, rainfall patterns during the preceding climatic phase of the Maldá Oscillation (1760–1800) were the direct opposite of those observed during the early 19th century. Additionally, the analysis of instrumental data shows a similar pattern of severe droughts between the end of the LIA and the current context of global warming. On the other hand, the 20th century does not show such a pattern for severe droughts.

The integration of historical documentary sources with instrumental records for identifying severe droughts has yielded promising outcomes. This methodology, leveraging documentary evidence, has been proven viable for periods or regions lacking instrumental data. Building on the success of merging these two climatic information sources, a prospective research direction for the early 19th century and other significant climatic epochs involves amalgamating historical data with evidence from other climatic proxies, particularly dendrochronology, alongside instrumental pressure series. Such an approach would enhance our comprehension of the atmospheric processes at a synoptic scale, elucidating the mechanisms behind the most severe drought episodes.

Data availability. The historical drought data used in this paper for the period 1790–1830 are presented in a database file (unpublished data). Note that the material related to the AMARNA database is still under analysis and is not yet ready for release or publication. It is possible that it will become available in the future, but at the time of writing this information cannot be accessed by the general public.

Author contributions. JB: data processing and analysis, interpretation of the results, and preparation of graphic and cartographic material. MH: general revision of the text and advice on the preparation of the materials. SGG: methodological approach and advice on the conceptual criteria for defining drought. JOC: general review and advice on the conceptual criteria for defining drought. MB: elaboration and organization of information from historical sources.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Acknowledgements. This article has made been possible thanks to the support provided by the following grants and institutions:

- "Ayudas para estudios de Máster oficial e iniciación a la investigación (AII)", University of Alicante;
- "Ajuts Joan Oró per a la contractació de personal investigador predoctoral en formació (FI)", year 2023. Government of Catalonia;
- "Grupo de investigación de Agua y Territorio", University of Alicante;
- "Grupo de Clima y Ordenación del Territorio", University of Alicante;
- "Departamento de Análisis Geográfico Regional y Geografía Física", University of Alicante.

Financial support. This research has been supported by the Universidad de Alicante (Ayudas para estudios de Máster oficial e iniciación a la investigación (AII)) and Ajuts Joan Oró per a la contractació de personal investigador predoctoral en formació FI – 2023 (AGAUR) under file code 2023 FI-1 00518 from CREAF at the Autonomous University of Barcelona.

Review statement. This paper was edited by Julie Loisel and reviewed by Marzena Kłusek and one anonymous referee.

References

AEMET e Instituto de Meteorología de Portugal: Atlas Climático Ibérico, Madrid, 79 pp., https://www.aemet.es/documentos/es/conocermas/recursos_en_linea/publicaciones_y_estudios/publicaciones/Atlas-climatologico/Atlas.pdf (last access: 15 March 2024), 2011.

Alberola, A.: El clima "trastornat": sequera, temporals, riuades i inundacions a Catalunya i al País Valencià a les acaballes del segle XVIII. Estudis d'història Agrària, 23, 301–317, http://www.raco.cat/index.php/EHA/article/view/259564 (last access: 21 November 2015), 2010.

Alberola, A. and Arrioja, L.: Clima, medio ambiente y plagas de langosta en la Península Ibérica y América Central en el último tercio del siglo XVIII, Una aproximación comparativa, Anuario de Estudios Atlánticos, 65, 1–23, http://hdl.handle.net/10045/86896 (last access: 18 November 2024), 2018.

Alcoforado, M. J., Nunes, M. de F., Garcia, J. C., and Taborda, J. P.: Temperature and precipitation reconstruction in southern Portugal during the late Maunder Minimum (AD 1675–1715), Holocene, 10, 333–340, https://doi.org/10.1191/095968300674442959, 2000.

Azcárate, I. (Ed.): Plagas agrícolas y forestales en España (s. XVIII–XIX), Serie Estudios no. 131, Ministerio de Agricultura, Pesca y Alimentación, Madrid, Spain, 439 pp., ISBN 84-491-0270-7, 1996.

Barriendos, M.: El clima histórico de Catalunya. Aproximación a sus características generales (ss. XV–XIX), PhD thesis, Department of Physical Geography, University of Barcelona, Spain, 499 pp., https://dialnet.unirioja.es/servlet/tesis?codigo=240591 (last access: 18 November 2024), 1994.

Barriendos, M.: El clima histórico de Catalunya (siglos XIV–XIX), Fuentes, métodos y primeros resultados, Rev. Geograf. 30–31, 69–96, 1996.

Barriendos, M.: Climatic variations in the Iberian Peninsula during the late Maunder minimum (AD 1675–1715): An analysis of data from rogation ceremonies, Holocene, 7, 105–111, https://doi.org/10.1177/095968369700700110, 1997.

Barriendos, M.: Variabilidad climática y riesgos climáticos en perspectiva histórica. El caso de Catalunya en los siglos XVIII–XIX, Rev. Hist. Modern., 23, 11–34, 2005.

Barriendos, M. and Barriendos, J.: Los inicios de la Pequeña Edad del Hielo en España. Aportaciones de la climatología histórica al clima del siglo XIV, Geographicalia, 73, 55–79, https://doi.org/10.26754/ojs_geoph/02108380, 2021.

Barriendos, M. and Llasat, M. C.: The case of the “Maldá” anomaly in the Western Mediterranean basin (AD 1760–1800): An example of a strong climatic variability, Climatic Change, 61, 191–216, https://doi.org/10.1023/A:1026327613698, 2003.

Barriendos, M. and Martín-Vide, J.: Secular climatic oscillations as indicated by catastrophic floods in the Spanish Mediterranean coastal area (14th-19th centuries), Climatic Change, 38, 473–491, https://doi.org/10.1023/A:1005343828552, 1998.

Barriendos, M. and Sánchez Rodrigo, F.: Study of historical flood events on Spanish rivers using documentary data, Hydrolog. Sci. J., 51, 765–783, https://doi.org/10.1623/hysj.51.5.765, 2006.

Barriendos, M., Gil-Guirado, S., Pino, D., Tuset, J., Pérez-Morales, A., Alberola, A., Costa, J., Balasch, J. C., Castelltort, X., Mazón, J., and Ruiz-Bellet, J. L.: Climatic and social factors behind the Spanish Mediterranean flood event chronologies from documentary sources (14th–20th centuries), Global Planet. Change, 182, 102997, https://doi.org/10.1016/j.gloplacha.2019.102997, 2019.

Bentabol, H.: Las aguas de España y Portugal, Vda. e Hijos de M. Tello, 2nd edtion, 1900, Reissue El Viso, Madrid, Spain, 347 pp., 1900.

Bravo-Paredes, N., Gallego, M. C., Domínguez-Castro, F., García, J. A., Vaquero, J. M.: Pro-pluvia rogation ceremonies in Extremadura (Spain): Are they a good proxy of winter NAO?, Atmosphere, 11, 282, https://doi.org/10.3390/atmos11030282, 2020.

Brázdil, R., Glaser, R., Pfister, C., Antoine, J. M., Barriendos, M., Camuffo, D., Deutsch, M., Enzi, S., Guidoboni, E., and Rodrigo, F. S.: Flood events of selected rivers of Europe in the Sixteenth Century, Climatic Change, 43, 239–285, 1999.

Brázdil, R., Kiss, A., Luterbacher, J., Nash, D. J., and Řezníčková, L.: Documentary Data and the Study of Past Droughts: A Global State of the Art, Clim. Past, 14, 1915–1960, https://doi.org/10.5194/cp-14-1915-2018, 2018.

Brázdil, R., Demarée, G. R., Kiss, A., Dobrovolný, P., Chromá, K., Trnka, M., Dolák, L., Reznícková, L., Zahradnícek, P., Limanowka, D., and Jourdain, S.: The extreme drought of 1842 in Europe as described by both documentary data and instrumental measurements, Clim. Past., 15, 1861–1884, https://doi.org/10.5194/cp-15-1861-2019, 2019.

Brönnimann, S., White, S., and Slonosky, V.: Climate from 1800 to 1970 in North America and Europe, in: The Palgrave Handbook of Climate History, edited by: White, S., Pfister, C., and Mauelshagen, F., Palgrave Macmillan, London, UK, 309–320, https://doi.org/10.1057/978-1-137-43020-5_25, 2018a.

Brönnimann, S., Pfister, C., and White, S.: Archives of Nature and Archives of Societies, in: The Palgrave Handbook of Climate History, edited by: White, S., Pfister, C., and Mauelshagen, F., Palgrave Macmillan, London, UK, 27–35, https://doi.org/10.1057/978-1-137-43020-5_3, 2018b.

Camuffo, D., Bertolin, C., Diodato, N., Cocheo, C., Barriendos, M., Domínguez-Castro, F., Garnier, E., Alcoforado, M. J., and Nunes, M. F.: Western Mediterranean precipitation over the last 300 years from instrumental observations, Climatic Change, 117, 85–101, https://doi.org/10.1007/s10584-012-0539-9, 2013.

Cook, E. R., Seager, R., Kushnir, Y., Briffa, K. R., Büntgen, U., Frank, D., Krusic, P. J., Tegel, W., Van der Schrier, G., Andreu-Hayles, L., Baillie, M., Baittinger, C., Bleicher, N., Bonde, N., Brown, D., Carrer, M., Cooper, R., Čufar, K., Dittmar, C., Esper, J., Griggs, C., Gunnarson, B., Günther, B., Gutierrez, E., Haneca, K., Helama, S., Herzig, F., Heussner, K. U., Hofmann, J., Janda, J., Kontic, R., Köse, N., Kyncl, T., Levanič, T., Linderholm, H., Manning, S., Melvin, T. M., Miles, D., Neuwirth, B., Nicolussi, K., Nola, P., Panayotov, M., Popa, I., Rothe, A., Seftigen, K., Seim, A., Svarva, H., Svoboda, M., Thun, T., Timonen, M., Touchan, R., Trotsiuk, V., Trouet, V., Walder, F., Ważny, T., Wilson, R., and Zang, C.: Old World megadroughts and pluvials during the Common Era, Sci. Adv., 1, e1500561, https://doi.org/10.1126/sciadv.1500561, 2015.

Couchoud, R.: Hidrología histórica del Segura, Efemérides hidrológica y fervorosa recopilada y escrita por el Dr. R. Couchoud, DL: M-8457-1965, Centro de Estudios Hidrográficos, Madrid, Spain, 104 pp., 1965.

Cuadrat, J. M., Alfaro Pérez, F. J., Tejedor Vargas, E., Barriendos, M., and Serrano-Notivoli, R.: La megasecada de 1626–1635 i els seus impactes a la vall mitjana de l’Ebre (Espanya), Estudis d’Història Agrària, 34, 163–183, https://doi.org/10.1344/eha.2022.34.163-183, 2022.

Domínguez-Castro, F., Santisteban, J. I., Barriendos, M., and Mediavilla, R.: Reconstruction of seasonal and annual rainfall variability in the Iberian Peninsula (16th–20th Centuries) from documentary data, Global Planet. Change, 63, 230–242, https://doi.org/10.1016/j.gloplacha.2008.06.002, 2008.

Domínguez-Castro, F., Ribera, P., García-Herrera, R., Vaquero, J. M., Barriendos, M., Cuadrat, J. M., and Moreno, J. M.: Assessing extreme droughts in Spain during 1750–1850 from rogation ceremonies, Clim. Past., 8, 705–722, https://doi.org/10.5194/cp-8-705-2012, 2012.

Domínguez-Castro, F., Alcoforado, M. J., Bravo-Paredes, N., Fernández-Fernández, M. I., Fragoso, M., Gallego, M. C., García Herrera, R., Garnier, E., Garza-Merodio, G., El Kenawy, A. M., Latorre, B., Noguera, I., Peña-Angulo, D., Reig-Gracia, F., Silva, L. P., Vaquero, J. M., and Vicente Serrano, S. M.: Dating historical droughts from religious ceremonies, the international pro pluvia rogation database, Sci. Data, 8, 186, https://doi.org/10.1038/s41597-021-00952-5, 2021.

Erfurt, M., Skiadaresis, G., Tijdeman, E., Blauhut, V., Bauhus, J., Glaser, R., Schwarz, J., Tegel, W., and Stahl, K.: A multidisciplinary drought catalogue for southwestern Germany dating back to 1801, Nat. Hazards Earth Syst. Sci., 20, 2979–2995, https://doi.org/10.5194/nhess-20-2979-2020, 2020.

Eslamian, S., Ostad-ali-askari, K., Singh, V. P., and Dalezios, N. R.: A Review of Drought Indices, Int. J. Civ. Eng., 3, 48–66, https://doi.org/10.20431/2454-8693.0304005, 2017.

Espín-Sánchez, J. A., and Gil-Guirado, S.: Praying for rain, resilience, and social stability in Murcia (southeast Spain), Ecol. Soc., 27, 9, https://doi.org/10.5751/ES-12875-270209, 2022.

Fang, S.-W., Sigl, M., Toohey, M., Jungclaus, J., Zanchettin, D., and Timmreck, C.: The role of small to moderate volcanic eruptions in the early 19th century climate, Geophys. Res. Lett., 50, e2023GL105307, https://doi.org/10.1029/2023GL105307, 2023.

Fischer, E., Luterbacher, J., Zorita, E., Tett, S., Casty, C., and Wanner, H.: European climate response to tropical volcanic eruptions over the last half millennium, Geophys. Res. Lett., 34, L05707, https://doi.org/10.1029/2006GL027992, 2007.

Fragoso, M., Carraça, M. D. G., and Alcoforado, M. J.: Droughts in Portugal in the 18th century: A study based on newly found documentary data, Int. J. Climatol. 38, 5522, https://doi.org/10.1002/joc.5745, 2018.

Garnier, E.: Historic Drought from archives: Beyond the Instrumental Record, in: Drought Science and Policy, edited by: Iglesias, A., Assimacopoulos, D., and Van Lanen, H. A. J., Wiley-Blackwell, 45–67, https://doi.org/10.1002/9781119017073.ch3, 2019.

Garza-Merodio, G. G.: Variabilidad climática en México a través de fuentes documentales (siglos XVI al XIX), Instituto de Geografía, UNAM – Universidad Nacional Autónoma de México, https://www.cervantesvirtual.com/obra/variabilidad-climatica-en-mexico-a-traves-de-fuentes (last access: 18 November 2024), 2017.

Gibbs, W. J. and Maher, J. V.: Rainfall Deciles as Drought Indicators, Bureau of Meteorology Bull. 48, Commonwealth of Australia, Melbourne, Australia, https://www.scirp.org/reference/referencespapers?referenceid=2819353 (last acces: 1 March 2024), 1967.

Gil-Guirado, S.: Reconstrucción climática histórica y análisis evolutivo de la vulnerabilidad y adaptación a las sequías e inundaciones en la Cuenca del Segura (España) y en la cuenca del Río Mendoza (Argentina), PhD thesis, Department of Geography of the University of Murcia, Spain, 749 pp., http://hdl.handle.net/10201/36964 (last access: 3 September 2022), 2013.

Gil-Guirado, S. and Pérez-Morales, A.: Climatic variability and temperature and rainfall patterns in Murcia (1863–2017). Climate analysis techniques in the context of global change, Investigaciones Geograficas, 71, 27–54, https://doi.org/10.14198/INGEO2019.71.02, 2019.

Gil-Guirado, S., Espín-Sánchez, J. A., and Prieto, M.: Can we learn from the past? Four hundred years of changes in adaptation to floods and droughts. Measuring the vulnerability in two Hispanic cities, Climatic Change, 139, 183–200, https://doi.org/10.1007/s10584-016-1768-0, 2016.

Gil-Guirado, S., Gómez-Navarro, J. J., and Montávez, J. P.: The weather behind words–new methodologies for integrated hydrometeorological reconstruction through documentary sources, Clim. Past., 15, 1303–1325, https://doi.org/10.5194/cp-15-1303-2019, 2019.

Gil-Guirado, S., Olcina-Cantos, J., and Pérez-Morales, A.: The blessing of the “year without summer”: Climatic and socioeconomic impact of the Krakatoa eruption (1883) in the southeast of the Iberian Peninsula, Int. J. Climatol., 41, 2279–2300, https://doi.org/10.1002/joc.6958, 2021.

Global Volcanism Program: Volcanoes of the World (v. 5.1.5; 15 Dec 2023), Distributed by Smithsonian Institution, compiled by: Venzke, E., Smithsonian Institution, https://doi.org/10.5479/si.GVP.VOTW5-2023.5.1, 2023.

Gorostiza, S., Martí Escayol, M. A., and Barriendos, M.: Controlling water infrastructure and codifying water knowledge: institutional responses to severe drought in Barcelona (1620–1650), Clim. Past, 17, 913–927, https://doi.org/10.5194/cp-2020-33, 2021.

Grove, J. M.: The Little Ice Age, Routledge, ISBN 0-415-01449-2, 1988.

IDMP: Drought and water Scarcity, WMO No. 1284, Global Water Partnership, Stockholm, Sweden and World Meteorological Organization, Geneva, Switzerland, ISBN 978-92-63-11284-2, 2022.

IPCC: Annex II: Glossary, in: Climate Change 2022: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., and Rama, B., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2897–2930, https://doi.org/10.1017/9781009325844.029, 2023.

Kim, W. and Raible, C. C.: Dynamics of the Mediterranean droughts from 850 to 2099 CE in the Community Earth System Model, Clim. Past., 17, 887–911, https://doi.org/10.5194/cp-17-887-2021, 2021.

Lee, D. S. and MacKenzie, A. R.: Trans-hemispheric effects of large volcanic eruptions as recorded by an early 19th century diary, Int. J. Climatol., 30, 2217–2228, https://doi.org/10.1002/joc.2034, 2010.

Lloyd-Hughes, B. and Saunders, M. A.: A drought climatology for Europe, Int. J. Climatol., 22, 1571–1592, https://doi.org/10.1002/joc.846, 2002.

Luterbacher, J. and Pfister, C.: The year without a summer, Nat. Geosci., 8, 246–248, 2015.

Marcos-Garcia, P., Lopez-Nicolas, A., and Pulido-Velazquez, M.: Combined use of relative drought indices to analyze climate change impact on meteorological and hydrological droughts in a Mediterranean basin, J. Hydrol., 554, 292–305, https://doi.org/10.1016/j.jhydrol.2017.09.028, 2017.

Martín-Vide, J.: Pluges i inundacions a la Mediterrània, Ketres Editora, Barcelona, Spain, 132 pp., ISBN 84-85256-44-1, 1985.

Martín-Vide, J. and Barriendos, M.: The use of rogation ceremony records in climatic reconstruction: a case study from Catalonia (Spain), Climatic Change, 30, 201–221, https://doi.org/10.1007/BF01091842, 1995.

Martín-Vide, J. and Olcina Cantos, J.: Climas y tiempos de España, Alianza Editorial, Madrid, Spain, 176 pp., ISBN 84-206-5777-8, 2001.

Mathbout, S., Lopez-Bustins, J., Royé, D., Martín-Vide, J., and Benhamrouche, A.: Spatiotemporal variability of daily precipitation concentration and its relationship to teleconnection patterns over the Mediterranean during 1975–2015, Int. J. Climatol., 40, 1435–1455, https://doi.org/10.1002/joc.6278, 2020.

McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to time scales, in: Proceedings of the 8th Conference on Applied Climatology, 17–22 January 1993, Anaheim, USA, 179–183, 1993.

Mishra, A. K. and Singh, V. P.: A review of drought concepts, J. Hydrol., 391, 202–216, https://doi.org/10.1016/j.jhydrol.2010.07.012, 2010.

MITECO – Ministerio para la Transición Ecológica y el Reto Demográfico: Cuencas y subcuencas hidrográficas, https://www.miteco.gob.es/en/cartografia-y-sig/ide/descargas/agua/cuencas-y-subcuencas.aspx (last access: 5 June 2023), 2023.

Moruno, C.: La sequera de 1817 a Catalunya. Abast i conseqüències socials en un context de postguerra. Estudis d'història Agrària, 32, 97–113, https://doi.org/10.1344/eha.2020.32.97-113, 2021.

Nalbantis, I.: Evaluation of a Hydrological Drought Index, European Water, 2324, 67–77, 2008.

Olcina, J.: Tipología de sequías en España, Ería, 56, 201–227, 2001a.

Olcina, J.: Causas de las sequías en España. Aspectos climáticos y geográficos de un fenómeno natural, in: Causas y consecuencias de las sequías en España, edited by: Gil Olcina, A. and Morales Gil, A., Gráficas Antar, S.L., Alicante, Spain, 49–110, ISBN 84-7908-600-9, 2001b.

Oliva, M., Ruiz-Fernández, J., Barriendos, M., Benito, G., Cuadrat, J. M., Domínguez-Castro, F., García-Ruiz, J. M., Giralt, S., Gómez-Ortiz, A., Hernández, A., López-Costas, O., López-Moreno, J. I., López-Sáez, J. A., Martínez-Cortizas, A., Moreno, A., Prohom, M., Saz, M. A., Serrano, E., Tejedor, E., Trigo, R., Valero-Garcés, B., and Vicente-Serrano, S. M.: The Little Ice Age in Iberian mountains, Earth-Sci. Rev., 177, 175–208, https://doi.org/10.1016/j.earscirev.2017.11.010, 2018.

PAGES Hydro2k Consortium: Comparing proxy and model estimates of hydroclimate variability and change over the Common Era, Clim. Past, 13, 1851–1900, https://doi.org/10.5194/cp-13-1851-2017, 2017.

Pauling, A., Luterbacher, J., Casty, C., and Wanner, H.: Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation, Clim. Dynam. 26, 387–405, https://doi.org/10.1007/s00382-005-0090-8, 2006.

Pfister, C.: Evidence from the Archives of Societies: Institutional Sources, in: The Palgrave Handbook of Climate History, edited by: White, S., Pfister, C., and Mauelshagen, F., Palgrave Macmillan, London, UK, 67–81, https://doi.org/10.1057/978-1-137-43020-5_6, 2018.

Pfister, C. and White, S.: A Year Without a Summer, 1816, in: The Palgrave Handbook of Climate History, edited by: White, S., Pfister, C., and Mauelshagen, F., Palgrave Macmillan, London, UK, 551–561, https://doi.org/10.1057/978-1-137-43020-5_35, 2018.

Posit team: RStudio: Integrated Development Environment for R, Posit Software, PBC, Boston, MA, http://www.posit.co/ (last access: 15 July 2024), 2024.

Prohom, M.: Incidència de les grans erupcions volcàniques en el clima de la península Ibèrica i Balears, PhD thesis, Department of Physical Geography, University of Barcelona, Spain, 226 pp., http://hdl.handle.net/2445/41968 (last access: 16 May 2024), 2003.

Prohom, M., Barriendos, M., and Sanchez-Lorenzo, A.: Reconstruction and homogenization of the longest instrumental precipitation series in the Iberian Peninsula (Barcelona, 1786–2014), Int. J. Climatol., 36, 3072–3087, https://doi.org/10.1002/joc.4537, 2016.

Raible, C. C., Brönnimann, S., Auchmann, R., Brohan, P., Frölicher, T., Graf, H. F., Jones, P., Luterbacher, J., Muthers, S., Robock, A., Self, S., Sudrajat, A., Timmreck, C., and Wegmann, M.: Tambora 1815 as a test case for high impact volcanic eruptions: Earth system effects, Wires Clim. Change, 7, 569-589, https://doi.org/10.1002/wcc.407, 2016.

Ramírez-Vega, M. D.: Sequías, plagas de langosta y crisis agrícola en el virreinato de Nueva España, 1765–1780, PhD thesis, Colegio de Michoacan, CONAHCYT, Mexico, 335 pp., http://colmich.repositorioinstitucional.mx/jspui/handle/1016/1140 (last access: 3 October 2023), 2021.

Rico y Sinobas, M.: Memoria sobre las causas meteorológico-físicas que producen las constantes sequías de Murcia y Almería, señalando los medios de atenuar sus efectos, Imprenta a cargo de D. S. Compagni, Madrid, Spain, 391 pp., https://www.bibliotecadigitaldeandalucia.es/catalogo/es/consulta/registro.do?id=1016172 (last access: 18 November 2024), 1851.

Rodrigo, F. S.: Cambio climático natural: la pequeña edad de hielo en Andalucía. Reconstrucción del clima histórico a partir de fuentes documentales, PhD thesis, Department of Applied Physics, University of Granada, Spain, 393 pp., http://hdl.handle.net/10481/37533 (last access: 6 June 2023), 1994.

Rodrigo, F. S. and Barriendos, M.: Reconstruction of seasonal and annual rainfall variability in the Iberian peninsula (16th–20th centuries) from documentary data, Global Planet. Change, 63, 243–257, https://doi.org/10.1016/j.gloplacha.2007.09.004, 2008.

Rodrigo, F. S., Esteban-Parra, M. J., and Castro-Diez, Y.: An Attempt to Reconstruct the Rainfall Regime of Andalusia (Southern Spain) from 1601 A.D. to 1650 A.D. using historical documents, Climatic Change, 27, 397–418, https://doi.org/10.1007/BF01096269, 1994.

Rodrigo, F. S., Esteban-Parra, M.J., and Castro-Diez, Y.: Reconstruction of Total Annual Rainfall in Andalusia (Southern Spain) During the 16th and 17th Centuries from Documentary Sources, Theor. Appl. Climatol., 52, 207–218, https://doi.org/10.1007/BF00864044, 1995.

Rodrigo, F. S., Esteban-Parra, M. J., and Castro-Diez, Y.: On the use of the Jesuit order private correspondence records in climate reconstructions: a case study from Castille (Spain) for 1634–1648 A.D., Climatic Change, 40, 625–645, https://doi.org/10.1023/A:1005316118817, 1998.

Sánchez-Almodóvar, E., Martín-Vide, J., Olcina-Cantos, J., and Lemus-Canovas, M.: Are Atmospheric Situations Now More Favourable for Heavy Rainfall in the Spanish Mediterranean? Analysis of Episodes in the Alicante Province (1981–2020), Atmosphere, 13, 1410, https://doi.org/10.3390/atmos13091410, 2022.

Serrano-Notivoli, R., Martín-Vide, J., Saz, M. A., Longares, L. A., Beguería, S., Sarricolea, P., Meseguer-Ruiz, O., and de Luis, M.: Spatio-temporal variability of daily precipitation concentration in Spain based on a high-resolution gridded data set, Int. J. Climatol., 38, e518–e530, https://doi.org/10.1002/joc.5387, 2018.

Sivakumar, M. V. K., Motha, R. P., Wilhite, D. A., and Wood, D. A. (Eds.): Agricultural Drought Indices, in: Proceedings of the WMO/UNISDR Expert Group Meeting on Agricultural Drought Indices, 2–4 June 2010, Murcia, Spain, AGM-11, WMO/TD No. 1572, WAOB-2011, World Meteorological Organization, Geneva, Switzerland, 197 pp., https://www.droughtmanagement.info/literature/WMO_agricultural_drought_indices_proceedings_2010.pdf (last access: 14 October 2021), 2011.

Stagge, J. H., Kohn, I., Tallaksen, L. M., and Stahl, K.: Modeling drought impact occurrence based on meteorological drought indices in Europe, J. Hydrol., 530, 37–50, https://doi.org/10.1016/j.jhydrol.2015.09.039, 2015.

Steinemann, A. C., Hayes, M. J., and Cavalcanti, L. F.: Drought indicators and triggers, in: Drought and Water Crises: Science, Technology, and Management Issues, edited by: Wilhite, D. A., CRC Press, 71–92, http://danida.vnu.edu.vn/cpis/files/Refs/Drought/DroughtIndicatorsandTriggers.pdf (last access: 23 February 2023), 2005.

Tejedor, E., De Luis, M., Barriendos, M., Cuadrat, J. M., Luterbacher, J., and Saz, M. Á.: Rogation ceremonies: A key to understanding past drought variability in northeastern Spain since 1650, Clim. Past, 15, 1647–1664, https://doi.org/10.5194/cp-15-1647-2019, 2019.

Trigo, R. M., Vaquero, J. M., Alcoforado, M. J., Barriendos, M., Taborda, J., Garcia-Herrera, R., and Luterbacher, J.: Iberia in 1816, the year without summer, Int. J. Climatol., 29, 99–115, https://doi.org/10.1002/joc.1693, 2009.

Tsakiris, G., Pangalou, D., and Vangelis, H.: Regional drought assessment based on the Reconnaissance Drought Index (RDI), Water Resour. Manage., 21, 821–833, https://doi.org/10.1007/s11269-006-9105-4, 2007.

Tuset, J., Barriendos, M., and Barriendos, J.: Historical Floods on the Spanish Mediterranean Basin: A Methodological Proposal for the Classification of Information at High Spatio-Temporal Resolution – AMICME Database (CE 1035–2022), Land, 11, 2311, https://doi.org/10.3390/land11122311, 2022.

Van Loon, A. F.: Hydrological drought explained, WIRES Water, 2, 359–392, https://doi.org/10.1002/wat2.1085, 2015.

Van Loon, A. F. and Van Lanen, H. A. J.: A process-based typology of hydrological drought, Hydrol. Earth Syst. Sci., 16, 1915–1946, https://doi.org/10.5194/hess-16-1915-2012, 2012.

Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index, J. Climate, 23, 1696–1718, https://doi.org/10.1175/2009JCLI2909.1, 2010.

Wagner, S. and Zorita, E.: The influence of volcanic, solar and CO_2 forcing on the temperatures in the Dalton Minimum (1790–1830): A model study, Clim. Dynam., 25, 205–218, https://doi.org/10.1007/s00382-005-0029-0, 2005.

Wilhite, D. A. and Glantz, M. H.: Understanding the drought phenomenon: The role of definitions, Water Int., 10, 111–120, https://doi.org/10.4324/9780429301735-2, 1985.

WMO – World Meteorological Organization: Drought, https://public.wmo.int/en/resources/world-meteorological-day/previous-world-meteorological-days/climate-and-water/drought (last access: 6 June 2023), 2023.

WMO and GWP – World Meteorological Organization and Global Water Partnership: Handbook of Drought Indicators and Indices, in: Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2, edited by: Svoboda, M. and Fuchs, B. A., Geneva, 52 pp., ISBN 978-92-63-11173-9, 2016.

Xoplaki, E., Luterbacher, J., Wagner, S., Zorita, E., Fleitmann, D., Preiser-Kapeller, J., Sargent, A. M., White, S., Toreti, A., Haldon, J. F., Mordechai, L., Bozkurt, D., Akçer-Ön, S., and Izdebski, A: Modelling climate and societal resilience in the Eastern Mediterranean in the last millennium, Hum. Ecol., 46, 363–379, https://doi.org/10.1007/s10745-018-9995-9, 2018.

Zamora Pastor, R.: El final de la “Pequeña Edad del Hielo” en tierras alicantinas, University of Alicante, Alicante, Spain, 196 pp., 2002.

Zargar, A., Sadiq, R., Naser, B., and Khan, F. I.: A review of drought indices, Environ. Rev., 19, 333–349, https://doi.org/10.1139/a11-013, 2011.